Proceedings of the 25th International Workshop on Optical Wave & Waveguide Theory and Numerical Modelling

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BASTIAAN PIETER DE HON and SANDER JOHANNES FLORIS
Eindhoven University of Technology

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Department of Electrical Engineering
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June 2017

Eindhoven University Press
Eindhoven University of Technology
Eindhoven, the Netherlands
https://www.tue.nl

Proceedings of the 25th International Workshop on Optical Wave & Waveguide Theory and Numerical Modelling

held on April $5^{\rm th}$ and $6^{\rm th}$ 2017
at Eindhoven University of Technology

B.P. de Hon and S.J. Floris
June 2017

ISBN: 978-90-386-4318-2

Programme and Table of Contents

Tuesday, 4 April, 19.30–20.30, Blue Collar Hotel

19.30–20.30 **Welcome reception. Opportunity to register and pick up workshop materials. The reception partly overlaps with the ECIO 2017 conference dinner.**

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8.00– 8.50 **Registration, coffee & tea outside the Cinema Hall**

8.50– 9.00 **Word of welcome**

9.00–10.30 **Oral Session OW1: *Optical Fibre Interfaces and Space Division Multiplexing***, chaired by **B.P. de Hon**

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OWP4 **Ö. Ö. Karakilinç***, Pamukkale University, Department of Electrical-Electronics Engineering, Denizli, Turkey, *Design of degenerate mode based photonic crystal add-drop filter.* 16

OWP5 **G. Altares Menendez*, B. Maes**, Micro- and Nanophotonic Materials Group, Faculty of Science, University of Mons, Belgium, *Time-modulated graphene arrrays for efficient frequency-comb generation with plasmonic resonances*, We propose a dynamically modulated graphene array to generate highly tunable frequency combs, by exploiting the significant frequency shifts of a plasmonic resonance. This mechanism requires Fermi level modulations that are smaller by 3 orders of magnitude than in the planar geometry introduced by Ginis et al. 17

OWP6 **A. Nerukh[1*], O. Kuryzheva[1], and T. Benson[2]**, [1]Kharkov National University of Radio Electronics, Kharkov, Ukraine, [2]George Green Institute for Electromagnetics Research, University of Nottingham, Nottingham, United Kingdom, *Time-spatial structure of Airy pulse in non-stationary environment*, A complex phenomenon including an asymmetric time varying Airy pulse and an asymmetric time varying bounded medium is considered. It is shown that this phenomenon is controlled by a generalised start parameter determined by the point of the source location and the moment of its initiation. 18

OWP7 **V.A. Burdin[1*], A.V. Bourdine[1,2]**, [1]Povolzhskiy State University of Telecommunications and Informatics (PSUTI), Samara, Russia, [2]LLC "OptoFiber Lab", Skolkovo Innovation Center, Moscow, Russia, *The necessary conditions of nonlinear excitation of high order modes in single mode optical fibres*, The necessary conditions of nonlinear excitation of high order modes in single mode optical fibre are considered in this paper. The calculation results of dependence of exciting power for optical pulse from normalized frequency of step-index optical fibre are presented. 19

OWP8 **A.-L. Fehrembach[*1], K. Sharshavina[1], F. Lemarchand[1], E. Popov[1], A. Monmayrant[2], P. Arguel[2], O. Gauthier-Lafaye[2]**, [1]Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France, [2]LAAS-CNRS, Université de Toulouse, CNRS, UPS, Toulouse, France, *2x1D crossed gratings for polarization independent tunable transmission filters*, In a previous work, we showed that the 2x1D crossed resonant gratings configuration was suitable for polarization independent reflection filtering tunable with respect to the angle of incidence [Opt. Lett. 36, 1662 (2011)]. In the present work, we adapt this concept to transmission filtering. This requires strongly modulated gratings and for the design, the use of an optimization algorithm combined with our in-house RCWA numerical code. 20

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10.40–11.00 **Coffee & tea in Auditorium Voorhof; removal of posters**

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11.20–11.40 OT2.2 **S. F. Helfert*, T. Seiler, J. Jahns**, FernUniversität in Hagen, Chair of Micro- and Nanophotonics, Hagen, Germany, *Numerical simulation of hollow waveguide arrays as polarization converting elements and experimental verification*, The Method of Lines was used to simulate the wave propagation in hollow waveguide arrays. The polarization characteristics were studied and compared with experimental results. 32

11.40–12.00 OT2.3 **A. Połatyński[1]*, S. Mingaleev[2], A. Marinins[3], D. de Felipe[4], M. Kleinert[4], M. Kresse[4], C. Zawadzki[4], N. Keil[4], A. Richter[1]**, [1]VPIphotonics GmbH, Berlin, Germany, [2]VPI Development Center, Minsk, Belarus, [3]School of Information and Communication Technology, KTH Royal Institute of Technology, Stockholm, Sweden, [4]Fraunhofer Heinrich-Hertz Institute, Berlin, Germany, *Novel MxN three-dimensional MMI simulation model*, In this paper, a novel modelling method for 3D multimode interference (MMI) structures is presented. We have demonstrated the physical model and performance of a 16x16 3D MMI. The simulation results are based on self-imaging phenomena in multimode waveguides. 33

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13.30–13.50 OT3.1 **C. Arlotti*, O. Gauthier-Lafaye, S. Calvez**, Laboratoire d'Analyse et d'Architecture des Systèmes, Université de Toulouse, CNRS, UPS, Toulouse, France, *Spectral engineering of the transmission characteristics of racetrack resonators*, We report the study of the transmission characteristics of a vertically-coupled racetrack resonator as a function of the design of its constituting waveguides. We show that the use of asymmetric couplers can lead to quasi-critical coupling over a large spectral range and thus be useful for Kerr frequency comb generation. . . . 35

13.50–14.10 OT3.2 **L. Macé[1,2*], O. Gauthier-Lafaye[2], A. Monmayrant[2], H. Camon[2], H. Leplan[1], B. Portier[1]**, [1]Safran Reosc, Saint-Pierre-du-Perray, France, [2]LAAS-CNRS, Université de Toulouse, CNRS, Toulouse, France, *Modelisation of zero-contrast grating filters for pixelated applications in the mid-IR range*, In this paper, we report a way to adapt zero-contrast grating (ZCG) filters [1] to mid-IR multi-spectral applications by increasing their bandwidth and angular tolerance by a decade or more. For a central wavelength of 4.95µm, we achieve a filter's bandwidth of 38nm, compatible with 120µm pixel-sizes. . . . 36

14.10–14.30 OT3.3 **R. Kumar, A. Sharma***, Department of Physics, Indian Institute of Technology Delhi, New Delhi, India, *Bidirectional modelling of fiber Bragg gratings*, Modelling of fiber Bragg gratings (FBG) presents a challenge due to periodic reflections involved in the propagation. Although methods for bidirectional propagation for planar structures have been developed, dealing with cylindrical or two-dimensional structure still presents difficulty due to excessive computational effort. We discuss two approaches to propagation in periodic fibers, FBGs. . . . 37

14.30–14.50 OT3.4 **M. M. R. Elsawy, G. Renversez***, Aix–Marseille Univ, CNRS, Ecole Centrale Marseille, Institut Fresnel, Marseille, France, *Extremely enhanced figure of merit in nonlinear plasmonic waveguides in the C-band using metamaterials and a nonlinear active medium*, We propose new nonlinear plasmonic slot waveguide NPW using available materials that achieves the highest reported FOM among both plasmonic and all-dielectric nonlinear waveguides. Our new NPW can be a building block for ultra-compact photonic devices working in the telecommunication C-band. . . . 38

14.50–15.00 **Closing remarks**

Preface

The 25th International Workshop on Optical Wave & Waveguide Theory and Numerical Modelling (OWTNM) was held on April 5th & 6th, 2017 at Eindhoven University of Technology, Eindhoven, the Netherlands, in co-location, and in part jointly with the 19th edition of the European Conference on Integrated Optics.

The workshop certainly lived up to its international credentials, with authors and participants from Belarus, Belgium, Canada, China, the Czech Republic, Denmark, France, Germany, Greece, India, Italy, Netherlands, Russia, Spain, Sweden, Taiwan, Turkey, Ukraine, United Kingdom, and United States.

General topics of interest for the OWTNM Workshop concern the physical understanding, the mathematical description, and the computational treatment of guided as well as non-guided optical waves and related effects in micro- and nanostructures.

In 2017, a special topic of interest was the computational and design aspects of optical-waveguide space division multiplexing. Nicolas Fontaine, an invited speaker from Nokia Bell Laboratories delivered a fascinating invited address on the design, fabrication, and characterization of all-fiber photonic lantern spatial multiplexers and their application in mode-multiplexed transmission systems. The two other invited speakers were Remco Stoffer from Phoenix Software, who explained how information relevant to generic photonic designs is stored in Process Design kits, enabling photonic synthesis into any supported technology, and John Arnold from the University of Glasgow, who discussed the use of invariants of integrable (or nearly-integrable) systems as carriers of information, and also took us to an excursion into new ideas regarding electric pulse propagation along neurons.

During the six oral sessions and a poster sessions, and the breaks in between we have had good discussions on the scientific advances in our field in an open and relaxed atmosphere. As per tradition, a Topical Collection (rolling release version of a Special Issue) of *Optical and Quantum Electronics* (Springer Journal OQE) has been set up, and is open for full-paper submissions related to the workshop.

OWTNM 2017 Short Papers

Leaky-mode resonant gratings on a fiber facet

M. Vanek, J. Ctyroky, P. Honzatko *

Institute of Photonics and Electronics, CAS, Chaberska 57, 182 51 Prague, Czech Republic

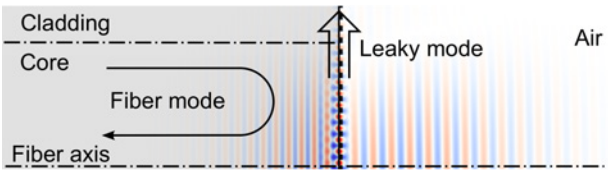
* *honzatko@ufe.cz*

We numerically investigate leaky-mode resonant diffraction gratings milled on the facet of optical fibers. The gratings are intended to be used as high-reflectivity polarizing mirrors in high-power fiber lasers. We compare plane-wave and fiber-mode diffraction efficiencies and optimize grating parameters for various fiber core diameters. The influence of the core diameter on the modal loss is discussed.

Introduction

Several approaches have been adopted to achieve a stable and defined polarization state at the output of fiber lasers without inserting any intracavity element which could impair the laser cost, reliability, lasing threshold and slope efficiency. Recently we reported on a polarizing, low-reflectivity diffraction grating milled on the facet of a large mode area optical fiber by a focused ion beam. The grating was experimentally tested as an output mirror of the high-power, thulium-doped fiber laser [1]. No deterioration in the slope efficiency or laser beam quality was observed, while the lasing threshold slightly increased as a result of modal loss of the component. The polarization extinction ratio decreased from 20 dB at low powers to 10 dB at high powers.

Here we report on a leaky-mode resonant diffraction grating that is intended to be employed as a high-reflectivity wavelength- and polarization-dependent mirror in a fiber laser. The grating is supposed to be milled into a high refractive index layer deposited on the fiber facet.



Coupling between the fiber mode and leaky-mode resonant grating.

Design of leaky-mode resonant gratings

The aperiodic rigorous coupled wave analysis, Fourier modal method and finite-difference time-domain method were used to compute the modal reflectivity of the investigated structures. Reflectivities approaching 100% were obtained theoretically when the depth of the grating grooves was sufficiently large. Under these conditions, strong coupling occurs between the fiber mode and the leaky mode which is guided in the high refractive index layer. High reflectivities can be achieved for large mode area fibers and even for standard fibers. The influence of fabrication tolerancies is discussed.

Acknowledgements

This work was funded by the Czech Science Foundation, grant GAP15-07908S.

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Simple and fast method for design spatial packaging scheme of MDM channels at FMF core end providing DMGD decreasing in few-mode fiber optic links

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This work presents fast and simple method for design mode division multiplexing (MDM) system channel precision spatial packaging scheme at few-mode optical fiber (FMF) core end. We utilize same approach known as "mode field matching centralized launching" technique [1, 2] that provides reducing differential mode group delay (DMGD) by equalization of launched and excited mode field radiuses (MFR). Unlike to known solutions it is proposed to localize combination of injected MFR and precision radial misalignment in relation to fiber core center that would provide transmission almost total injected MDM mode channel power to only one particular excited fiber mode with the same azimuthal order. Some results of computation launching parameters for 5-mode MDM multiplexer channels to the core end of earlier on designed FMF 42/125 under near- and far-field spatial packaging symmetric and asymmetric schemes are presented (please see Fig. 1).

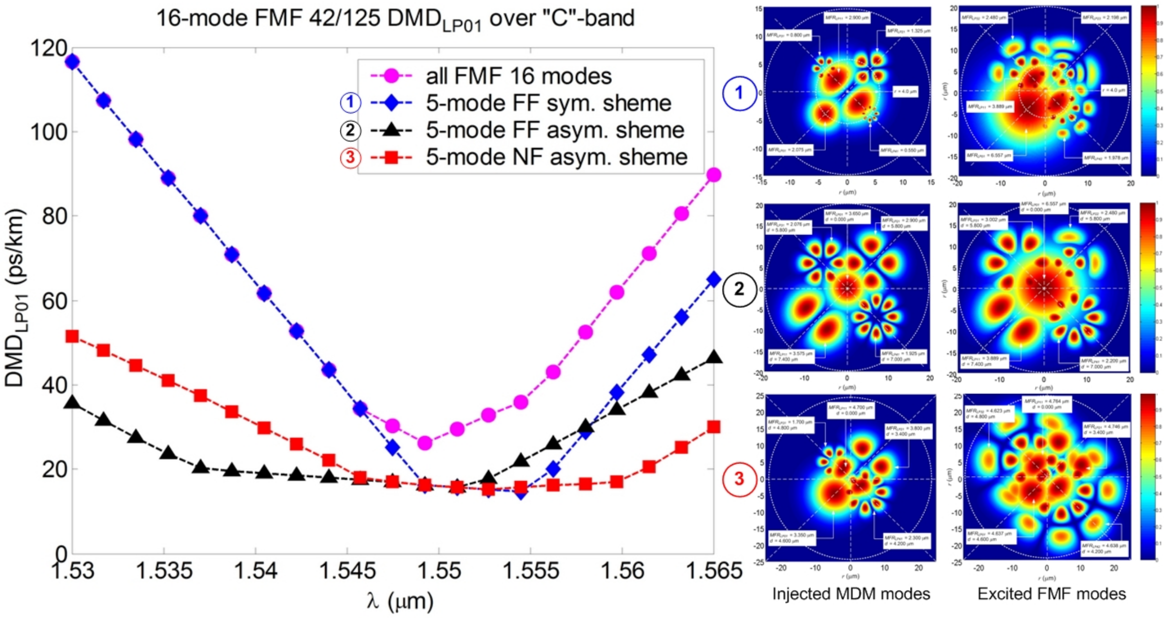

Figure 1. DMD curves over "C"-band for 16-mode low-DMD FMF 42/125 mode staff and under MDM 5-channel precision spatial packaging schemes providing selective mode field matching launching conditions

The reported study was funded by RFBR according to the research project No. 16-37-60015 mol_a_dk and

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A Wilson-Basis Approach to Electromagnetic Reflection-Transmission Problems involving Optical Fibers

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A Wilson basis with spatially-spectrally confined basis functions is well suited to expand modal electromagnetic fields, and to construct electromagnetic source distributions that generate one-way propagating fields in free space. We consider reflection-transmission field matching problems for optical fibers and homogeneous slabs.

Electromagnetic scattering problems involving fiber interfaces

Structured cabling installations in data centers require multiple connections in a link, driving the need for low loss connectors. The modal electromagnetic (EM) fields of multi-mode optical fibers are large compared to the wavelength, rendering reflection-transmission problems challenging. Existing modeling strategies for the scattering of an incident modal EM field on an interface of two fibers in physical contact are often based on approximation methods ignoring reflections [1] [2], and may not be adequate if more accurate results are required or if gaps are present. The modal power distribution in the receiving fiber is important for the performance of subsequent connections. Its accurate characterization is also valuable in the design of (few-mode) multi-mode fiber space division multiplexing (SDM) transmission systems.

Field expansion in a Wilson basis

The use of a Wilson basis with exponentially decaying functions and strong localization in both the spatial and spectral domain has convenient properties [3]. For instance, the spatial localization leads to a sparse translation operators, which is convenient in case of connections with lateral offset. Furthermore, the spectral localization aids the speed of convergence of the convolution integrals with Green's functions for the evaluation of EM fields due to Wilson-basis source distributions. In a fashion similar to the Poincaré-Steklov operator [4], we can show that specific linear combinations of electric and magnetic Wilson-basis source distributions exist that generate one-way propagating EM fields in a homogeneous space. This construction of equivalent sources may subsequently be employed in solving boundary-value problems for interfaces between two homogeneous half-spaces, fiber and a homogeneous half-space, and two fibers with a gap. For two fibers in physical contact, the Wilson expansion is still useful, but equivalent sources may no longer be required. In the full paper, we shall elaborate on reflection-transmission problems involving fibers and homogeneous space in a Wilson basis, e.g. for a free-space terminated optical fiber, the numerically determined return loss matches the laboratory measurements to within 0.1 dB, which is better than expected.

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Photonic Lanterns for Space-Division Multiplexed Communications

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Space-division multiplexing (SDM) using all modes of a multimode fiber requires mode multiplexers can simultaneously excite well over 10 spatial modes with low insertion loss and mode-dependent loss. We describe design, fabrication, and characterization of all-fiber photonic lantern spatial multiplexers and their application in mode-multiplexed transmission systems.

Photonic lanterns have emerged as the most promising mode-multiplexer in SDM optical communications. They can losslessly separate N modes from a multimode fiber into N separated fibers [1, 2]. They are fabricated by tapering a preform comprising many fibers inside a low index capillary until the individual fiber cores vanish and no longer guide light and a new multimode core is formed by the fiber claddings and the low index capillary. Their all-fiber constructions enables direct splicing from the lantern to the multimode transmission fiber and the adiabatic transition reduces fabrication tolerances and allows for ultra-wideband operation. They can be analyzed by computing the eigenmodes of the refractive index profile at each diameter.

There are three levels of mode selectivity useful in SDM systems in order of easiest to the most difficult to fabricate: 1) scrambling, 2) mode-group selective, and 3) mode-selective. Mode-selectivity is tailored by inserting fibers with different propagation constants into the capillary. We will present 15 spatial mode devices and highlight record transmission results that fiber photonic lanterns have enabled.

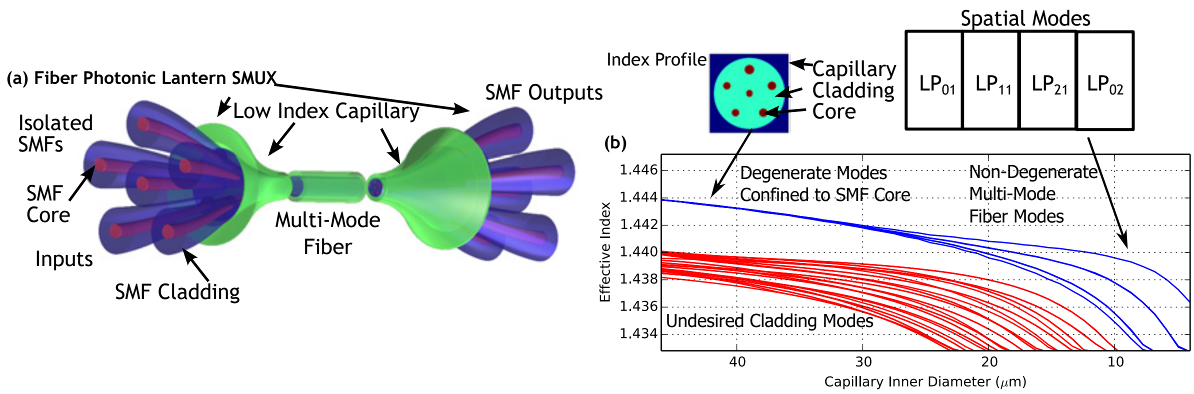

Fig. 1. (a) All-Fiber Photonic Lantern (b) Propagation constants vs. taper diameter

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One-dimensional bi-periodic dielectric photonic crystals

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We investigate the transmittivity spectra of the electromagnetic waves for the one-dimensional (1D) dielectric photonic crystals (PCs) with two periods, created on basis of three different oxides. The modifications of the spectra with the change of the period numbers, layers thicknesses and incidence angle are considered.

Bi-periodic PC and the transmission spectra

The 1D bi-periodic PCs present a new promising class of photonic structures. First these systems were proposed for the photonic-magnonic crystals [1, 2] and investigated as photonic hypercrystals [3].

In this communication we present study of the photonic band gap (PBG) spectra of the electromagnetic waves propagating through the 1D dielectric bi-periodic PCs $[(1/2)^N 3]^M$ with the layers 1, 2 and 3 chosen to be the dielectric oxides TiO_2, SiO_2 and Al_2O_3, respectively, which are transparent within the visible and near infrared regimes. The first period $D_0 = d_1 + d_2$ refers to the alternating layers TiO_2 and SiO_2 of the thicknesses d_1 and d_2. The second period $D_1 = N(d_1 + d_2) + d_3$, is formed by the repeating Al_2O_3 layers of the thickness d_3 [see Fig. 1(a)].

The modifications of the TE- and TM-modes spectra within the first PBG and its vicinity with the change of N and M, and the incidence angle θ is considered. The PBG spectra of both TE- and TM-modes exhibits a set of defect modes (DMs). The number of DMs is correlated with the period number M [Figs. 1 (b) and 1 (c)], while N strongly effects the DMs thicknesses. The increase of θ allows to shift the positions of both PBG edges and DMs to the higher frequencies, and to control the PBG width. Changing the layers thicknesses one can get significant shift of the DMs towards the PBG edges and also increase the number of the DMs inside the PBG.

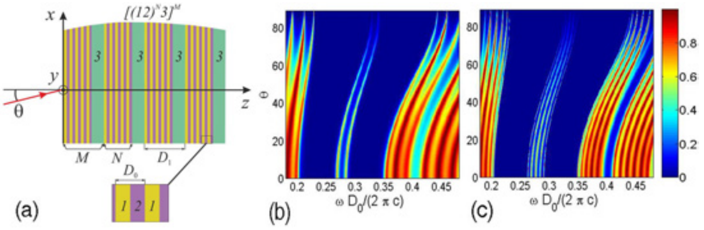

Fig.1. Schematic of the 1D bi-periodic PC (a). Transmittance of TE-modes vs the normalized frequency $\omega D_0/(2\pi c)$ for $((TiO_2/SiO_2)^3 Al_2O_3)^M$ with $M = 2$ (b) and $M = 5$ periods (c). The layer thicknesses are $d_1 = 0.199\,\mu m$, $d_1 = 0.341\,\mu m$ and $d_3 = 0.281\,\mu m$.

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Calculations of modes on dielectric substrate supported silver metallic nanowires: Circular versus pentagonal wire cross-section

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[1]*Graduate Institute of Photonics and Optoelectronics,* [2]*Department of Electrical Engineering, and*
[3]*Graduate Institute of Communication Engineering, National Taiwan University, Taipei 10617, Taiwan*
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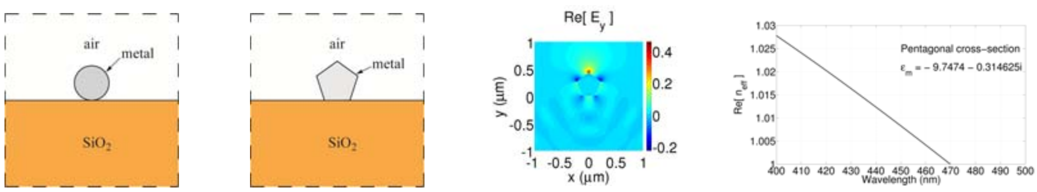
Plasmon modes, in particular the leaky modes, propagating on dielectric-substrate supported silver nanowires of circular and pentagonal cross-sections are numerically investigated using a finite-element method. Reliability in mode solutions is discussed by considering computing-window sizes.

Summary

An in-house developed full-vector finite-element imaginary-distance beam propagation method (FV-FE-IDBPM) has been employed to study and find the modes propagating on silver nanowires supported by a dielectric substrate. This analysis method has recently been used to provide high-resolution modal characteristics and detailed modal profiles of leaky modes on a related stripe plasmonic waveguide with a metal stripe fabricated on top of a substrate [1]. In this paper, nanowires of circular cross-sectional shape and those of pentagonal shape, as depicted in Fig. 1(a) and (b), respectively, are both considered. For the former, we have obtained leaky-mode solutions with modal electric field mainly localized on the top of the nanowire in the air along with down-propagating leakage field in the substrate. For the latter, numerical calculations are to be compared with the characteristics reported recently in [2]. Possible application in mode-division multiplexing for increasing data transmission channels along a pentagonal nanowire through the existence of multiple leaky plasmon modes was proposed in [2] where however the case involving three leaky modes was not discussed in detail. We will particularly investigate this case and carefully discuss the reliability in numerical mode calculations. When the wire width in Fig. 1(b) is around 454 nm, it was found in [2] that there exists three leaky modes at the wavelength $\lambda = 532$ nm with the real part of the effective index, Re[n_{eff}], of the third mode being smaller than unity. We will show that such below cutoff situation requires more careful examination. Fig. 1(c) shows the Re[E_y] profile of the third leaky mode near cutoff and Fig. 1(d) (Re[n_{eff}] vs. λ plot) shows that this mode becomes cutoff near $\lambda = 470$ nm under the assumption that the silver permittivity is fixed at that at $\lambda = 500$ nm.



(a) (b) (c) (d)

Fig. 1. (a) Cross-section of the circular nanowire with substrate. (b) Cross-section of the pentagonal nanowire. (c) Re[E_y] profile of the third leaky mode on the structure of (b) with nanowire width of 456.5 nm at $\lambda = 469.8$ nm. (d) Re[n_{eff}] *of the third leaky mode on the structure of (b) versus wavelength.*

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A 3D spatial-spectral integral equation method for electromagnetic scattering from finite objects in a layered medium.

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We present a generalization to 3D of an integral equation method for electromagnetic scattering from finite objects in a layered medium. We employ a complex-plane deformation two directions of the spectral domain and a normal-vector field approach for the field-material interaction in the spatial domain.

Introduction

For metrology in integrated circuit production, integrated optics and the design of metamaterials the use of numerical methods is important. With the increasing complexity of the structures in these fields, the demands on these numerical methods are increasing as well.

Although several highly efficient spectral methods exist for periodic structures, e.g. RCWA and spectral VIM [1], the applicability of such solvers to periodic objects limits the applicability of these solvers for non-periodic objects. Although local methods such as FEM and FDTD exist to solve for finite scattering objects, local methods do not fully exploit the translational symmetry found in a layered medium, so usecases exist where global methods that do exploit this translational symmetry (e.g. VIM) are more potentially efficient. The use of a spectral method has two advantages, the first one is that tedious Sommerfeld integrals in the calculation of the Green function can be avoided. The second advantage is that the spatial Green function convolution becomes a pointwise multiplication, which can be carried out in $O(N)$ instead of $O(N^2)$ calculation time needed for a convolution.

Description of the algorithm

We present a spatial-spectral method inspired by a spectral VIM for electromagnetic scattering in three dimensions from finite dielectric objects in three dimensions embedded in a layered medium. This algorithm is a generalization of the algorithm for two dimensions presented in [2,3]. The use of a Gabor frame as a discretization and a complex-plane path deformation in the spectral domain allow for a spectral multilayer Green function representation. In the change from two to three dimensions, the complex path changes in a 2D deformed plane, which is divided into nine regions of three unique types, where the one-dimensional Taylor series was replaced by sets of piecewise-linear interpolation functions. In the field-material interaction a normal-vector field formalism is introduced to deal with discontinuous scattering objects. The use of the spectral domain for the Green function multiplication and the spatial domain for the field-material interaction allows for an $O(N \log N)$ calculation time for the iterations in the BiCGStab(2) iterative solver we use.

We will give an overview of the key ingredients that make up this algorithm and show numerical results and compare them to FEM results.

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Modelling open nanophotonic structures using the Fourier modal method in infinite domains

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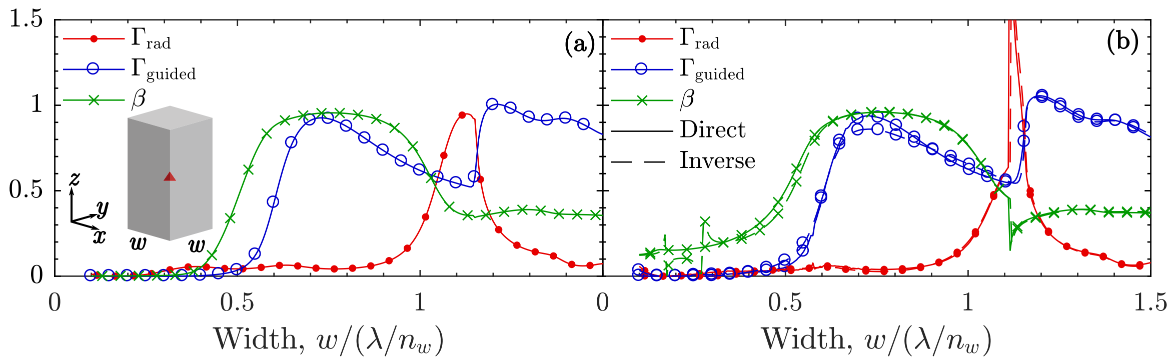
We present an open-geometry Fourier modal method (oFMM) for simulating nanophotonic structures in infinite domains with open boundary conditions. Our results show that a non-uniform sampling of the k-space is essential for convergence.

3D open geometry Fourier modal method

The Fourier modal method (FMM) in Cartesian coordinates uses Fourier series as the expansion basis. This implies periodic boundary conditions (BCs), which is advantageous for periodic structures like photonic crystals, however, the periodic BCs leads to parasitic reflections in open geometries from the leaky modes. This can be overcome by using absorbing boundaries, such as perfectly matched layers (PMLs), but convergence of PMLs towards an open geometry limit is generally not obtained. [1]. Instead of PMLs open boundary conditions can be used and recently this was developed for structures having cylindrical symmetry [2], where a non-uniform sampling of the k-space was shown to outperform the standard equidistant k-space discretization.



Normalised emission rates for an on-axis x-oriented dipole in an infinte square nanowire computed with (a) a non-uniform sampling and (b) using a standard equidistant sampling of the k-space.

In this work we have developed an open-geometry Fourier modal method with open boundary conditions in 3D Cartesian coordinates. Our results show that a non-uniform sampling of the k-space is essential to obtain good convergence especially for the leaky modes. This is seen in the figure, where the emission rate into the guided modes is well described with both discretization schemes, but the radiation modes are poorly described with the equidistant grid (b).

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Sidewall roughness in SiN-assisted flip-chip SiPh adiabatic coupling

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We numerically investigate the performance of the SiN-assisted SiPh adiabatic coupler for varying SiN layer thickness, considering the scattering losses at the chip edge, the taper tip and the Si waveguide sidewalls.

Concept and Simulation Results

During the last few years, adiabatic coupling between low-index waveguide platforms (polymer or glass boards) and Silicon Photonic (SiPh) integrated circuits has gained significant attraction, bearing the promise of enabling low-cost, low-loss and wavelength insensitive coupling to low-loss Photonic Circuit Boards and optical fibers, while several concepts have been proposed and realized towards this direction [1]. In the current manuscript, we numerically investigate the effect of the SiN layer on the performance of the SiN-assisted SiPh adiabatic coupling scheme, previously reported by the authors, considering chip edge and taper tip abrupt transition losses, together with the sidewall scattering losses of the tapered silicon waveguide. The simulated crossection is adapted to the flip-chip adiabatic coupling approach, employing a polymer board assembled on top of a SiPh chip, as shown in Fig. 1(a). The polymer core dimensions are 10μm x 5μm while the silicon chip employs a 220nm top-Si strip waveguide configuration, with 450nm nominal width and 2 degrees sidewall angle. The SiPh layer is cladded in a 520nm-thick LTO covered by a thin SiN layer. The separation distance between the polymer board and the SiPh chip is 100nm, filled with adhesive.
The design of the coupling interface relies on the constant loss taper (CLT) algorithm that ensures minimum coupling length for the targeted coupling efficiency [2]. The taper tip is chosen to be 50nm while the algorithm stops when it reaches the nominal silicon waveguide width. To investigate the effect of the SiN layer on the overall coupling efficiency, the algorithm was run iteratively for SiN thickness ranging between 0nm and 100nm and the respective CLT profiles were calculated as shown in Fig. 1(b). The different taper profiles were imported into a 3D EigenMode Expansion (EME) simulation environment, to calculate the coupling efficiency versus the taper length. The silicon scattering losses are modelled utilizing an extra thin absorbing layer on both waveguide sidewalls [3] inducing 2.5 dB/cm loss on the fundamental TE mode for the nominal Si waveguide width, while the chip edge abrupt transition losses are defined through overlap integral calculations at the SiPh chip end facet. The overall TE coupling efficiency versus taper length (for each SiN thickness) is depicted in Fig. 1(c), showing a maximum of 96% for 60 nm SiN layer thickness and 650 μm taper length.
Acknowledgments This work was partially supported by the EC projects SPIRIT (619603) and PICS4ALL (687777).

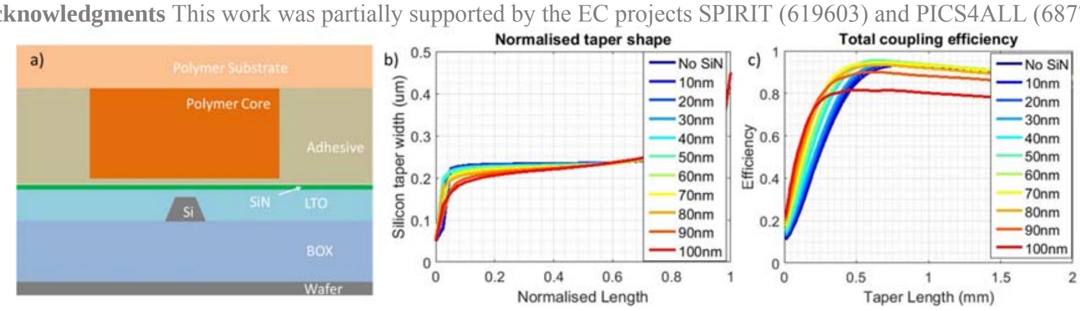

Fig.1.(a) Coupler crossection view, (b) Taper profiles versus normalised length and (c) Total efficiency versus length

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Implementing generic filter design in Process Design Kits

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This paper presents how information relevant to generic designs (exemplified by a filter) is stored in Process Design kits, enabling photonic synthesis into any supported technology.

Now that the photonic integrated circuit community and market are expanding rapidly, more and more entities start to offer their technology to the public. Over the last ten years, there has been a push toward capturing that technology in so-called PDKs, or Process Design Kits. PDKs contain information that a designer needs to create a design for that specific technology. Early PDKs contained only layout information (design intent and the mask layers that are associated with them, as well as building block (BB) layout information) and some rudimentary DRC (Design Rule Checking) rules, but they are maturing to contain much more complete information on the technology. For example, S-matrix or time domain circuit level models for all building blocks.

This presentation will focus on other information that is currently being put into PDKs, which will open up a standardized way of accessing data that a designer needs to design custom building blocks, without needing to do extensive simulations. As a vehicle for explaining this, we will use an MA lattice filter design module.

A lattice filter consists of a number of stages, each of which consisting of a coupler and a delay line (containing a component for setting the free spectral range, and an extra phase shift). Standard filter theory [1] allows to design a filter curve with a given free spectral range and filter curve, like interleavers or notch filters, by simply setting the correct values for the length of the delay lines and the coupling powers of the couplers. Thus, the PDK needs the following information in order to implement the layout of the filter:

- Group index and effective index (as a function of wavelength)

- A safe radius of curvature

- Building blocks that implement a coupler with a given coupling power. This can be a directional coupler whose gap or length are automatically set, or if the technology does not support a variable coupler but does support 50/50 splitters, it can be a slightly-imbalanced Mach-Zehnder interferometer.

The PDK thus requires hooks to set this information. The presentation will elaborate on how this is done in a standardized way.

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Oblique light propagation along bent slab waveguides

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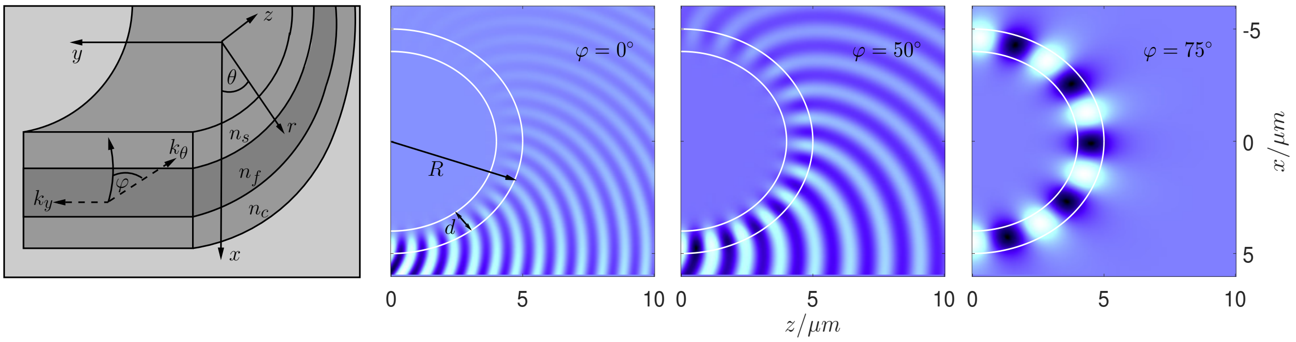
Segments of dielectric tubes support quasi-confined modes that propagate at oblique angles with respect to the axis of curvature. Our analytical model covers the full range of solutions from scalar TE/TM bend modes to lossless tube modes at near-axis propagation angles, with a continuum of vectorial spiral modes in between.

Spiral modes supported by dielectric tube segments

Waveguide bends are basic building blocks for various kinds of integrated photonic circuitry. Fundamental phenomena related to the waveguide curvature can be studied with analytical 2-D models [1] of bent slab waveguides with 1-D cross sections. These models assume that both the structure under investigation and the electromagnetic field are constant along the symmetry axis. Solutions are quasi-guided attenuated waves that propagate along the curved slab, in a direction perpendicular to the axis. In this contribution we reconsider the bent slab structures, now looking at quasi-guided waves that also have an axial wavenumber component. As hinted at in the figure, the curves given by the local wavevectors spiral around the central y-axis, hence we call these fields "spiral modes".



Spiral modes of a tube structure with radius $R = 5\,\mu$m, core thickness $d = 1\,\mu$m, and refractive indices $n_s : n_f : n_c = 1.6 : 1.7 : 1.6$, at a vacuum wavelength of $1.3\,\mu$m. Snapshots of transversal electric fields $\Re\{-\sin(\varphi)E_\theta(r) + \cos(\varphi)E_y(r)\}$ are shown, for modes at different angles of propagation φ.

Variations of the axial wavenumber parameter k_y translate to varying angles of propagation φ. The familiar 2-D bend modes are obtained for $k_y = 0$, with fields that are constant along y. For near-axial propagation, at φ close to $90°$, lossless waves can be expected that, for specific angles, and envisioning a continuation of the curved segment to a complete dielectric tube, form the guided modes supported by this tube-shaped optical fiber. In between, there is a continuum of vectorial waves, that propagate around the tube axis at varying angles, with varying levels of radiative losses. Our analytical models exploit the facilities for Bessel- and Hankel functions with complex order and argument as provided by the *Maple* computer algebra system. Examples for a series of radii and propagation angles will be discussed, for different levels of refractive index contrast.

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Simple coupling technique between active photonic chip and integrated silicon waveguide

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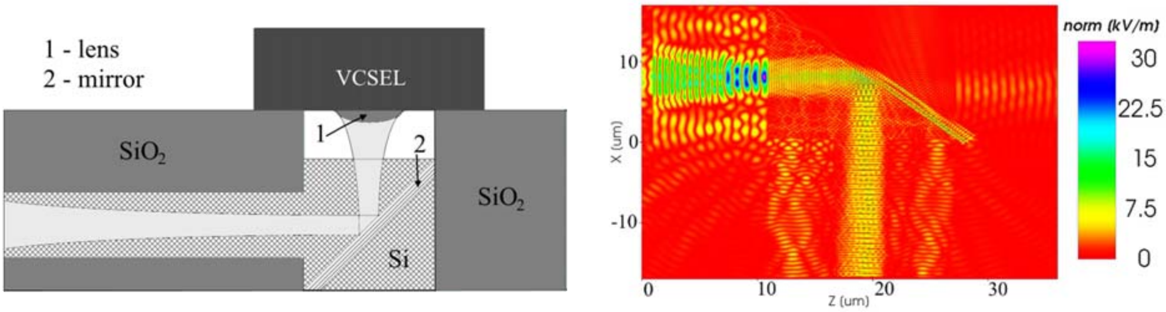
We propose and demonstrate a simple and practically efficient construction for coupling emission of LW-VCSEL to silicon waveguide. Following the simulation results, it provides the loss at a level near 5 dB. The construction is equally usable for a laser or photodiode coupler.

Last decade was characterized further important achievements in silicon photonics (SiP), which is a perspective platform for future large-scale photonic integrated circuits (PIC) [1]. Among other emerging semiconductor laser technologies, long-wavelength vertical cavity surface emitting lasers (LW-VCSELs), employing strained InP/InAlGaAs quantum well active regions, tunnel junction for carrier and optical confinement, and GaAs/AlGaAs distributed Bragg reflectors, have reached the industrial production stage and proven reliability [2]. A particular advantage of LW-VCSELs is their compatibility with silicon-based PICs [3].

One of the issue of a great importance is in enhancement of coupling efficiency between LW-VCSEL and integrated silicon waveguide. Although, up to date there are a number of advanced bonding constructions related with a flip-chip LW-VCSEL and a silicon grating coupler [4] but the total insertion loss is usually higher than 10 dB indicating an excess penalty of near 6 dB, compared to fibre-to-PIC coupling. In order to circumvent the above issue, we present a simple construction using a flip-chip LW-VCSEL with integrated lens 1 focusing laser beam and a well-known prism coupler with diagonal multilayer mirror 2 (Fig. 1a). Our initial simulation results using universal CAD tool OptoDesigner 5 from PhoeniX Software (Fig. 1b) show the coupling efficiency near 30% at the wavelength 1550 nm.



a) b)

Fig. 1. Conceptual diagram (a) and Electric field distribution (b)

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Fully tunable SOI filtering element for flexible-grid applications

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We propose and simulate a fully tunable Silicon-on-Insulator filtering element, relying on a 2^{nd} order Micro Ring Resonator equipped with three variable optical couplers, achieving 70.5 GHz bandwidth tunability.

Concept and Simulation Results

Flexible-grid architectures and network components are currently emerging as an auspicious alternative for addressing the ever-increasing need for bandwidth, through the generation and routing of superchannel data streams. In this context, integrated flexible filtering elements and MUX/DEMUX devices are coming up as the ensuing technological step towards future network deployments offering advanced on-chip functionality combined with reduced consumption and footprint [1]. In this manuscript, we extend our previously reported work on SOI MRR-based flexible filtering elements, tackling the bandwidth tunability limitations encountered by the MZI-assisted 2^{nd} order MRR layout [2]. To this end, the two fixed waveguide-to-ring couplers were replaced by thermo-optically (TO) tunable variable optical couplers (MZIs A and C), rendering the MRR-based MUX/DEMUX fully tunable with respect to the power coupled in and out of the two sub-MRRs, as seen in Fig. 1(a). This additional degree of freedom will both enhance the bandwidth tunability and reduce the spectral ripple appearing in the spectral response [2] to reasonable levels. On the other hand, such modification clearly increases the number of control signals needed to operate the device, rising the complexity. For this reason, the assumed electrodes of the 2^{nd} order MRR device were arranged into three individual groups as indicated by the color map presented in Fig. 1(a). The electrodes of each group are driven by the same control TO signal undergoing equal phase change. The yellow electrodes tune the bandwidth of the component, the blue electrodes shift the resonance whereas the green electrodes set the bias point of MZIs A and C thus altering the bandwidth tuning range of the component. Setting the TO phase of the green electrodes at 95^0 and increasing the TO phase of the yellow electrodes from 11^0 to 96^0, 70.5 GHz bandwidth tunability is achieved with insignificant extra losses or spectral ripple, as shown in Fig. 1(b). The respective extinction ratio varies between 53.2 dB and 21.3 dB whereas the FSR is 2.95nm as depicted in Fig. 1(c). The commercially available Filarete ASPIC software was employed for the simulations.

Acknowledgments This work was partially supported by the EC projects SPIRIT (619603) and PICS4ALL (687777).

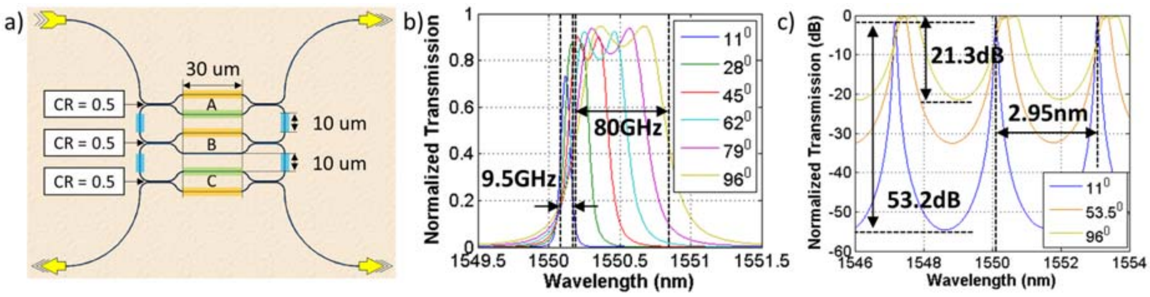

Fig.1.(a) Fully tunable filtering element layout, (b) Bandwidth tunabilty and (c) 2^{nd} order MRRs extinction ratios

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Design of degenerate mode based photonic crystal add-drop filter

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In this study, degenerate mode based photonic crystal (PhC) add-drop filter is proposed. Essential components of photonic crystal which are channel drop filters and coupled cavity waveguides are exploit the coupling of defect modes. The degeneracy of modes is broken with introducing a perturbation in the PhC microcavity. Then the defect modes have different frequency and splitted. By mode splitting, more frequency band is allowed in the resonance structure; hence the capability of signal processing is increased [1,2]. PhC microcavity exhibiting three bands characteristic that two of them has dual mode is proposed in this work. The microcavity constructed by a point defect and auxiliary perturbation rods are placed in two-dimensional (2D) square lattice PhC structure with alumina rods in air substrate as shown in the Figure. The simulated results show that the designed add-drop filter has the frequencies of 0.271 THz, 0.288 THz and 0.323 THz. Transmission characteristics can be changed by the structure properties of the perturbation rods and cavity rods. The proposed photonic crystal spectral filters structure can effectively be used for terahertz optical communication applications.

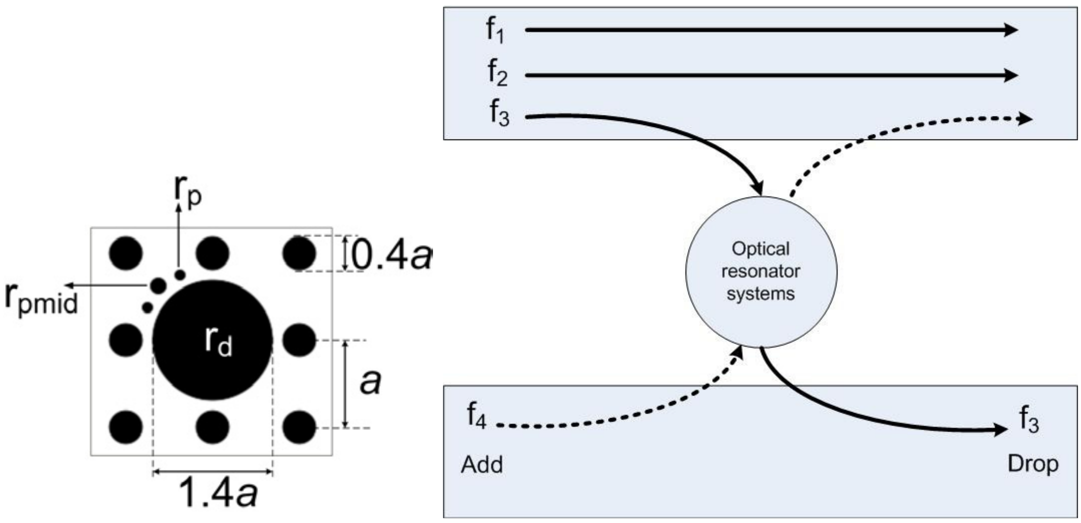

Figure: a) PhC microcavity (r_d, r_p, r_{pmid} are radius, a is lattice constant) b) Implementation of resonator structure in PhC

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Time-modulated graphene arrays for efficient frequency comb generation with plasmonic resonances

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We propose a dynamically modulated graphene array to generate highly tunable frequency combs, by exploiting the significant frequency shifts of a plasmonic resonance. This mechanism requires Fermi level modulations that are smaller by 3 orders of magnitude than in the planar geometry introduced by Ginis et al. [1].

Operation principle

We study a graphene nanoribbon array that supports localized graphene plasmon modes with a resonance frequency that strongly depends on the graphene Fermi level. By dynamically changing this Fermi level, the resonance frequency will in turn depend on time. As a result, monochromatic light couples to the plasmonic mode only when the incident light frequency matches the resonance frequency, acting as a shutter for incident light and leading to the generation of a frequency comb.

Methodology

We studied this structure using a simple CMT model to describe the plasmonic resonance and its modulation. We use rigorous Finite Element Method (FEM) simulations to extract the coupling coefficients, resonance frequency and time-dependent behaviour. The CMT model allows us to extensively study the intricate dynamics of the system. These approaches are in remarkable agreement, both in frequency and time-domain, allowing us to use the simple CMT model to study the comb generation properties of this setting. The overall result is that when a (nearly) monochromatic pulse is sent onto the time-dependent grating, a frequency comb is generated in transmission (Fig. 1). We analyze in detail how the grating, input and modulation parameters affect the final comb shape.

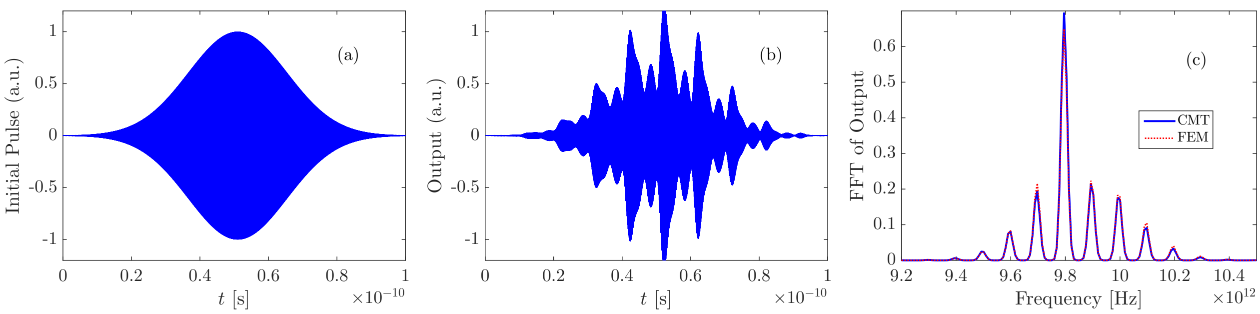

Fig. 1. (a) Pulse sent on the grating and (b) FEM result for the outgoing electric field in time domain. (c) FEM result for the output field (red) and CMT results for the output (blue) in frequency domain.

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Time-spatial structure of Airy pulse in non-stationary environment

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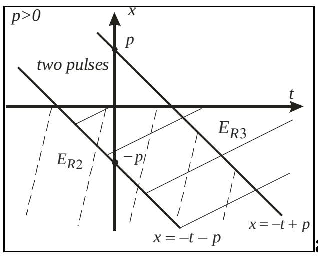
A complex phenomenon including an asymmetric time varying Airy pulse and an asymmetric time varying bounded medium is considered. It is shown that this phenomenon is controlled by a generalised start parameter determined by the point of the source location and the moment of its initiation.

Introduction

Interest in the paraxial propagation of optical Airy pulses is active for almost a decade due to their unusual properties [1]. At the same time interest in ordinary Airy pulses is not being lost due to their asymmetry form, especially if there is another asymmetry in the phenomenon. It may be caused by the medium boundary or by the non-stationarity of its features. This paper is devoted to the consideration of a substantially non-stationary phenomenon that is conditioned by the asymmetry of the initial Airy pulse $E_0(t,x) = \mathrm{Ai}(-t/T + x/vT - p)$, where $v = c/\sqrt{\varepsilon}$, ε is the permittivity of the undisturbed medium, and T is the scale factor. It is assumed that this pulse is generated by an extrinsic source which starts at the moment t_0 at the point x_0. These values determine the problem start parameter $p = (x_0/v - t_0)/T$. The asymmetry of the phenomenon takes new features if the refractive index changes at the zero moment to the value ε_1 in a dielectric half-space bounded by a plane.

Results

The solution to the problem which takes into account an asymmetric form of the initial signal and the non-stationarity of a bounded medium is solved by the Volterra integral equation method. It gives the transmitted pulse field which allows calculating the field of the reflected pulse consisting of three terms: $E_{R1}(t,x) = u(1-u)\mathrm{Ai}(ut/T + ux/vT - p)/(2(1+u))$, $E_{R2} = (1-u)\mathrm{Ai}(t/T + x/vT - p)/2$, $E_{R3} = -(1-u)\mathrm{Ai}(-t - x - p)/(1+u)$ where $u = \sqrt{\varepsilon/\varepsilon_1}$. The evolution of the reflected pulses E_{R2} and E_{R3} for two values of the start parameter $p = 5$ (a, b) and $p = -5$ (c, d) is illustrated in the diagram below. There is a stripe in the (t,x) coordinates with a very different field structure: the existence of two pulses (a, $p > 0$) and the absence of pulses (c, $p < 0$). The spatial distributions of the pulse field at $t = 0$ (dash) and $t = 10$ (solid) are also shown: (b, $p > 0$), (d, $p < 0$).



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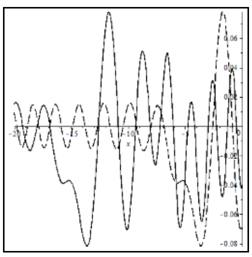
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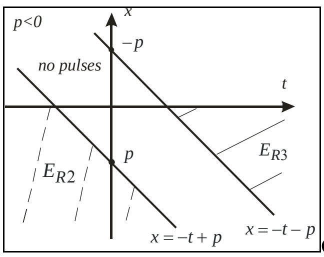

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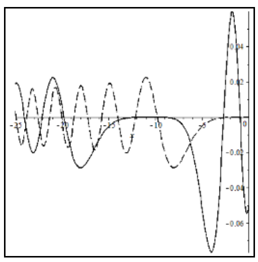
d)

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The necessary conditions of nonlinear excitation of high order modes in single mode optical fibres

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The necessary conditions of nonlinear excitation of high order modes in single mode optical fibre are considered in this paper. The calculation results of dependence of exciting power for optical pulse from normalized frequency of step-index optical fibre are presented.

In this paper we have tried to answer the questions of nonlinear excitation by examining the cut-off conditions changing for singlemode optical fibre due to the changing of the refractive index profile by the Kerr nonlinearity. Studies were carried out on an example of a step-index fiber with a cladding of pure fused silica glass and core of a fused silica glass doped with germanium. We considered the single-mode fibers. Without nonlinearity this optical fiber supports only the fundamental mode - LP01. For such optical fiber there were calculated the minimum values of an optical pulse power in the fiber for support LP11 mode. We studied the dependence of this power of the normalized frequency for the step-index fiber. This is a necessary condition but not sufficient. At some works is marked the instability of by the nonlinearity excited modes. Moreover, in the paper [1] is described the effect of the fundamental mode clearing in the multimode optical fiber due to the Kerr effect. Obviously, for the propagation of higher-order modes in single-mode fiber due to nonlinearity are required to fulfill additional conditions. To determine these sufficient conditions need to study the dynamics of the process of nonlinear modes propagation. However, pre-need to find the necessary conditions. This is the subject of this work, in which we limited the analysis of the necessary conditions for nonlinear excitation of higher order modes on the example of single mode optical fiber from fused silica glass. On the fig. 1 the dependence of threshold of the peak power of the optical pulse from normalized frequency of the step-index optical fibre for providing necessary conditions of nonlinear excitations LP11 mode is presented.

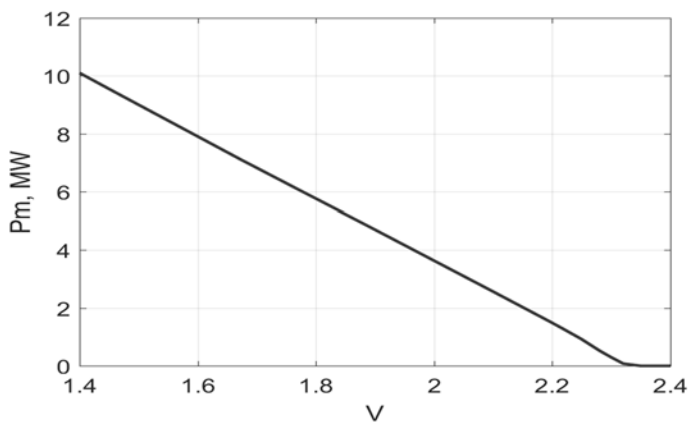

Figure 1. The dependence of threshold of the peak power from normalized frequency

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2x1D crossed gratings for polarization independent tunable transmission filters

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In a previous work, we showed that the 2x1D crossed resonant gratings configuration was suitable for polarization independent *reflection* filtering tunable with respect to the angle of incidence [Opt. Lett. 36, 1662 (2011)]. In the present work, we adapt this concept to *transmission* filtering. This requires strongly modulated gratings and for the design, the use of an optimization algorithm combined with our in-house RCWA numerical code.

Subwavelength gratings can exhibit narrowband resonance peaks in their scattering spectrum, known as Fano resonances [1]. One peak is due to the excitation of one mode of the structure through one evanescent diffraction order of the grating. The resonance wavelength is tunable with the angle of incidence. Moreover, 100% reflectivity or 100% transmittivity at resonance is ensured provided that the grating pattern fulfills symmetry conditions and that the materials are lossless. This 100% resonance is obtained for one given incident polarization, which depends on the configuration, and no resonance is observed for the polarization orthogonal to this given polarization [2].

In 2011, we proposed a 2x1D crossed gratings configuration that takes advantage on these properties to design a polarization independent narrowband spectral *reflection* filter tunable with the angle of incidence. The device was composed with two identical resonant all dielectric gratings separated with a thick substrate. The gratings directions are separated with an angle $90^\circ - \xi$ (see Fig. 1). Each half structure behaves as a reflection filter for one incident polarization and as an anti-reflective coating for the orthogonal polarization. The component shows more than 99% reflectivity at resonance whatever the incident polarization and a wide tunability of the centering wavelength (90 nm) around an optimum angle of incidence for which it reaches 100% reflectivity. The optimum angle of incidence depends on the angle ξ. More recently, we extended this idea to *transmission* filters [3]. In this case, each half structure must behave as a transmission filter for one incident polarization and as an anti-reflective coating for the orthogonal polarization, thus complicating the design of the device. To achieve the high reflectivity part of the transmission filter spectrum, we resort to a strongly modulated grating (engraved in a high index lossless material). To optimize the parameters, we combined an optimization algorithm (Global Clustering Optimization) with our in-house RCWA code.

The aim of the present communication is to provide a thorough comparison between the 2x1D crossed gratings reflection and transmission filters. We will show that for the reflection filter, the reflectivity maximum is obtained for linear polarizations given by the electric field of the modes of each half structure. On the contrary, for the transmission filter, the transmittivity maximum is obtained for elliptic polarizations. Hence, the spectral response of the whole structure can be foreseen from that of each half structure for the reflection filter but not for the transmission one.

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Design Bragg gratings based on subwavelength grating waveguides

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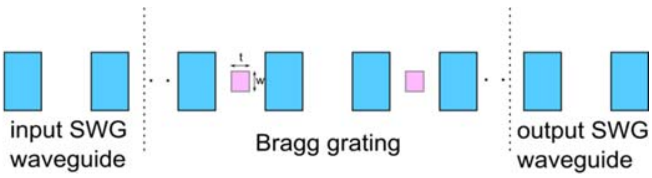
In this contribution, our recent results of numerical modelling of novel Bragg filter gratings based on subwavelength grating (SWG) waveguides are presented and discussed.

Introduction

As one of the promising alternative designs, proposed recently, within the silicon-on-insulator (SOI) integrated photonics platforms with high refractive index contrast between the silicon "core" and surrounding media, the subwavelength grating (SWG) waveguides, based on the alternative formation of the subwavelength sized (quasi)periodic structures and Bloch wave propagation concept, has been finding their perspective in many applications. Thus, the research efforts have concentrated on various functional elements such as couplers, crossings, mode transformers, MMIs, converters, resonators, and even narrow-band Bragg filters. The original concept of a Bragg SWG-based filter structure has consisted of two alternating segments, with slightly different widths, as was originally introduced in [1]. However, as was further shown [2], using a real 3D simulations, this original concept was technologically unrealizable, because of a very small segment width changes (in the order of 1 nm), required for a narrow band filter functioning.

Numerical modelling of SWG-based Bragg filter designs

In this work, we present 3D numerical analyses of various new configurations of narrow band Bragg filters, aiming at technological feasibility within the standard SOI technology. An example of such possible feasible configurations is shown together with the calculated spectra in Fig below. The Bragg function is obtained by adding a new element of size (t,w) (typically of 20 - 50 nm). To model spectral characteristics, two independent 3D in-house tools based on Fourier modal methods (aRCWA, BEX) were used. Different configurations of SWG-based Bragg filters will be discussed within the contribution.



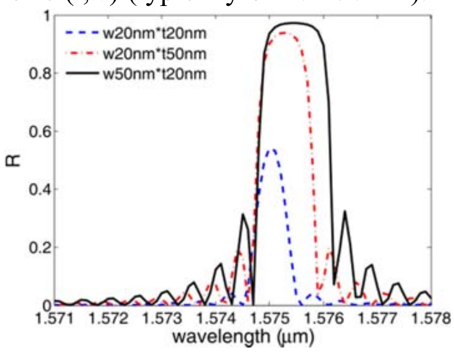


Fig. (a) Schematic drawing of one possible configuration of a Bragg filter grating based on SWG, (b) calculated spectra of the structure shown in (a); different sizes of a modulation element considered (structure consists of 1024 double periods, with the total Bragg grating length of 512 μm).

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Highly sensitive refractive index SPR sensor in IR region using indium tin oxide grating on gold film

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We present a highly sensitive refractive index sensor based on a grating engraved in indium tin oxide (ITO). Our study shows that ITO grating based sensor has a high sensitivity of 2400 nm/RIU with an FWHM of 50 nm. FWHM could be brought down to 15 nm by inserting a gold layer underneath the ITO grating.

Introduction

Surface Plasmon Resonance (SPR) sensors are very important for the detection of bio-molecules, bio-molecular interactions and medical diagnostics. Applications of SPR based sensors are limited in visible and UV regions due to interband electronic transitions in metal [1]. Indium tin oxide (ITO) supports the excitation of surface plasmons in IR region and can be employed in SPR sensors. Although, ITO coated thin film based optical fiber sensors are available, our prime focus in this paper is to study the performance of ITO grating assisted SPR sensor and to enhance its sensitivity by using gold layer underneath ITO grating.

Numerical simulations and results

Numerical simulations are carried out using rigorous coupled-wave analysis (RCWA). Theoretical results for the grating period Λ = 1200 nm, depth d = 75 nm are shown in Fig 1. It can be observed from Fig.1 (b) that the resonance wavelength changes as the refractive index ($1.32 < n_a < 1.36$) of the analyte is varied. The sensitivity of the sensor increases with increasing the incident angle. The maximum sensitivity of the sensor is 2400 nm/RIU, which is much higher than that obtained in the conventional metal grating-based sensors [2]. FWHM of the proposed ITO grating based sensor is about 50 nm and does not vary significantly with the refractive index of the analyte.

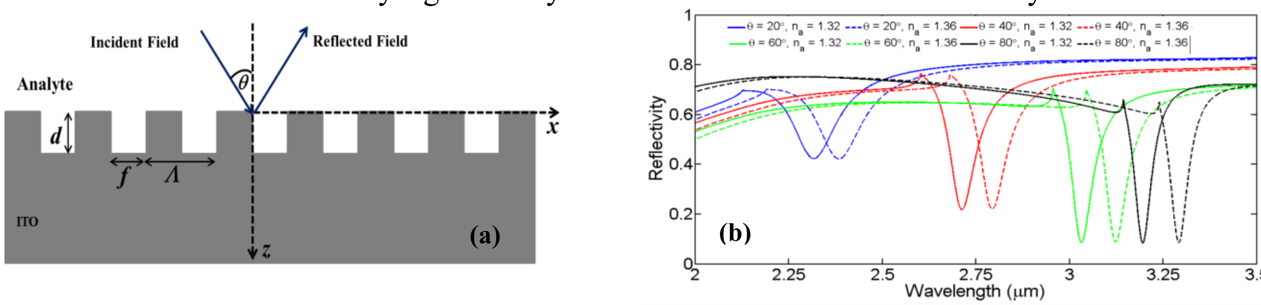

Fig.1 (a) Schamatic of the sensor and (b) SPR response of the sensor for different refreactive index (n_a) and incident angle (θ)

To reduce the FWHM, we developed a structure that consists of an ITO grating on gold layer. This brings down the FWHM to 15 nm while maintaing the sensitivity at 2400 nm/RIU and thus, improves that figure of merit of the sensor.

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Analysis of absorption in perfectly matched layer

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Collocation framework is used to analyze the modal and direct propagation in a dielectric structure bound by perfectly matched layer with the aim of analyzing the mechanism of the absorption of beam inside the perfectly matched layer (PML). Our results show that the modes are not orthogonal and that the modes of PML play a little or no role on absorption characteristics.

Summary

Perfectly matched layer was introduced to truncate the infinite transverse directions for reflection-less absorption, which further led to the discretization of infinite continuum of radiation modes [1]. It improved on earlier used absorbing boundary condition (ABC). There has also been interest to understand the modes of a PML bound structure [2]. We have used the collocation method to understand the role of these modes and to understand the mechanism of absorption in these layers. The collocation has the advantage that it provides both modal characteristics and the direct propagation analysis for a given dielectric structures [3]. Perfectly matched layer bound structures has been analyzed using variable transformation for propagation of beam.

As a test case we considered a tilted Gaussian beam which gets absorbed in the PML at the edge of the numerical window. We have obtained this propagation both by direct propagation and by considering sum of modes which include propagating, PML and evanescent modes. All modes are complex (see Fig. 1). We have found that these modes are not orthogonal; however, the propagation of their sum (see Fig. 2) matches well with the direct propagation. Another preliminary result that we have obtained that the PML modes play little or no role in determining the absorption behaviour of the layer. We are carrying out a similar analysis of the ABC. Further work is in progress and the results will be presented at the workshop.

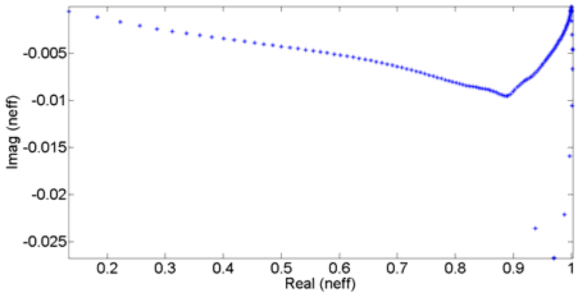

Fig.1 Effective indices of complex modes of a dielectric with index 1 bound at both ends with PML starting at 28μm and ending at 34.6μm. The wavelength is 1 μm.

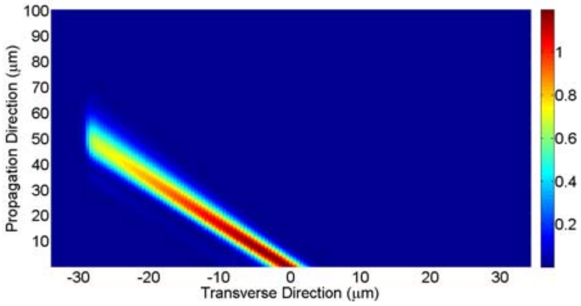

Fig.2 Propagation of a Gaussian beam at -30° with the direction of propagation obtained as a sum of modes.

This work was financially supported (for R.K.) by the University Grant Commission (UGC) Govt. of India.

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Design for efficient light absorption in microstructured silicon solar cell

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We have proposed a microstructure design for a silicon solar cell optimized for efficient light absorption. The study shows its validity over the entire AM1.5 spectrum. The proposed microstructure has been compared with the conventional planar p-n junction Solar Cell.

Summary

Microstructuring for enhanced light absorption in solar cells have attracted great interest, because the optical thickness of materials is generally high compared to the diffusion lengths [1]. Several novel structures have been proposed and analysed for enhanced and efficient light management [2-4]. Here we present a single p-n junction based Silicon Solar cell and have optimized the geometry for efficient light absorption over the entire range of wavelength. For optimizing, the angle 'A' was varied from 0º to 90º (see Fig. 1). The proposed structure consists of slanted parallel films of Silicon, with a transparent conducting oxide (Indium Tin Oxide) as conducting contacts on either side. Such structures can be realised by growing ITO pillars and depositing Si films on them. We have however carried out here only a two-dimensional analysis and Fig. 1 thus represents the cross section of the structure. Optimising parameters depend on the trade-off between maximizing path lengths for the incoming photon flux while minimizing the reflection loss governed by the Fresnel coefficients. Further, we have calculated the amount of flux contributing to the current by calculating the overlap integral of photon flux with the collection probability, varying across the junction. The collection probability distribution depends on the solar cell parameters, like doping density, intrinsic carrier concentration, temperature etc. The solar cell dimensions were taken as the sum of diffusion lengths and the depletion region. In our case, it turned out to be 45 μm. An optically thick length of 1mm was considered for the analysis. We optimized the slant angle to (24º -26º) for the entire wavelength range, further we observe light guidance by TIR for slant angles less than 62º. It may be noted that a fraction of the reflected light from the slant region shall also contribute to the photon flux on the adjacent structure, however, that has not been included here and will be included subsequently.

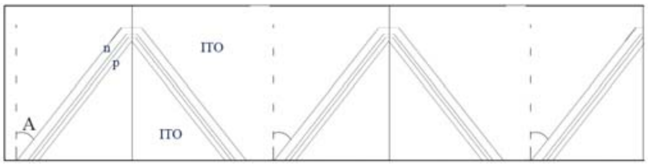

Fig. 1: Schematic of the microstructured geometry

We observe from Fig. 2 that about 25% increase in the converted photon flux by optimizing the angle and that factor increased further to 32.5% due to TIR guidance of the light incident at the top edge of the pillar.

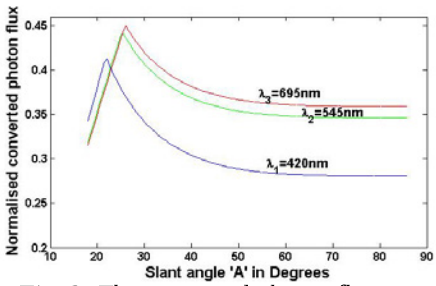

Fig. 2: The converted photon flux as a function of slant angle. The saturated value for 90 deg corresponds to the planar geometry.

This work was financially supported (for S.S.) by the University Grant Commission (UGC) Govt. of India.

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Estimation of power coupled into multi-moded surface plasmon waveguides: effect of power non-orthogonality of modes

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For estimating the total power coupled into the waveguide one has to take into account the cross modal terms arising due to the fact that the modes are not power orthogonal. We have illustrated the procedure by evaluation of the total coupled power in the excitation of two moded plasmonic waveguide by a dielectric waveguide in SOI configuration and nanoholes by a plane wave.

Over the recent years, surface plasmon waveguides have been extensively studied to realize sub-wavelength confinement in photonic nano-circuits. An array of periodic nanoscale holes [1] on a thin metal sheet has been found to exhibit extraordinary transmission properties. These arrays can be considered as an array of a few-moded surface plasmon waveguides, often formed by coupling between nearest neighbor interactions. Hence, it is important to estimate the total power coupled into such plasmonic waveguides from a given incident field. The excitation coefficient for the individual modes supported by plasmonic waveguides can be evaluated by the use of their mode orthogonality. However, these lossy modes are not power orthogonal. Hence, for estimating the total power coupled into the waveguide one has to take into account the cross modal terms arising due to the fact that the modes are not power orthogonal. We have first illustrated the procedure by evaluation of the total coupled power in the excitation by a (Si) on silicon oxide (SiO_2) dielectric waveguide of the modes of a two moded multi-layer plasmonic waveguide configuration formed by loading the Si on SiO_2 waveguide with an air-gold-silicon-nitride (Si_3N_4) plasmonic waveguide. Such a configuration has been shown earlier to act as a TE pass polarizer [2] with high extinction ratio in a very short spatial extent. Next the power coupled into of the nano-holes in a thin metal sheet by a plane wave has been considered in terms of excitation of the few mode plasmonic waveguides.

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Nanoporous anodic alumina optical biosensing modelling with 3D-FDTD

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Using a numerical procedure based on 3D FDTD, reflectance simulations of a nanoporous alumina photonic structure covered with a layer of gold were made for different configurations of its structural parameters, showing the possibility to be used as an optical biosensor.

Nanoporous anodic alumina (NAA) is a very interesting nanomaterial because of their optical, physical and chemical properties. One of its possible applications is as an optical biosensor on the basis of the measurement of changes in optical properties upon the detection of a biological species. The optical properties of NAA depend of their geometric characteristics (interpore distance, pore diameter, barrier layer thickness, etc.) which are strongly influenced by the fabrication conditions (acid electrolyte, anodization voltage or current, pH and temperature) [1]. Numerical methods for optical modelling such as the transfer-matrix method are not adequate since cannot take into account features such as the texturization of the metal-oxide interface, the great range of interpore distances, or the inhomogeneities in the chemical composition of the oxide. A numerical procedure based on 3D-FDTD permits to take into account all the geometrical and composition features, and simulate the optical properties of the structure [2].

We apply this procedure to the evaluate the sensitivity of NAA-based nanostructures in order to detect the binding of a biological-related molecule to the surface of the pores. Figure 1 shows the NAA structure and obtained results. The structure consists of a NAA thin film with a 20 nm thick superficial coating of gold. Figure 1.a shows the top and the cross section view SEM images, and figure 1.b shows a schematic picture of the geometric model. The bound molecule is modeled by considering a second 10 nm conformal coating with a refractive index slightly different than the medium filling the pores. The spectrum in figure 1.c shows a sharp reflectance valley around 880 nm, which shifts with the refractive index of the second coating. Along with a sensitivity study, this valley shift demonstrates the possibility of using the structure as a sensor.

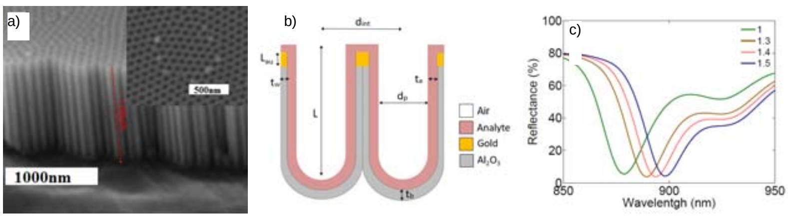

Figure1: Study of sensing with a gold-coated NAA film.

Acknowledgements

This work work was supported in part by the Spanish Ministry of Economy and Competitiveness TEC2015-71324-R (MINECO/FEDER), the Catalan authority AGAUR 2014SGR1344, and ICREA under the ICREA Academia Award.

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Design of Plasmonic Antennas for Wireless Optical Network on Chip

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Wireless optical networks have been recently proposed to connect Multi Processors directly at chip level. The efficient implementation of these links requires accurate design of antennas and waveguide to antenna couplers. In this work, some plasmonic antennas optimized for on-chip communications will be illustrated and discussed.

Introduction

On-chip communication through wireless optical networks is a recent approach proposed to overcome the bottleneck of wired communication in the state-of-the-art Chip Multi Processors (CMPs). This approach has some advantages with respect to the use of optical waveguide interconnects, though simplification of the network topology, reduction of loss and crosstalk. However, it brings also new and additional issues to be addressed, such as the design of efficient antennas and waveguide to antenna couplers, in order to optimize the performance of the wireless link. In this work, design of some plasmonic antenna for wireless optical on chip interconnects will be presented and discussed.

Results

As an example, a silicon waveguide coupled to a Vivaldi antenna is illustrated. The design of this structure requires the optimization of both the antenna and the coupling between the feeding waveguide and the radiating structure. For this purpose, the Finite Difference in the Time Domain (FD-TD) method can be profitably used. The figure illustrates the results obtained for the structure sketched in the left panel. A silicon waveguide is used to feed the plasmonic Vivaldi antenna located on the top. The center panel shows the Surface Radiation of the device, obtained through Near to Far Field transformation at $1550\ nm$. The right panel is the Radiation Diagram on the horizontal x, y plane. The calculated directivity is of $12\ dB$, which is promising to implement efficient optical links at a chip level.

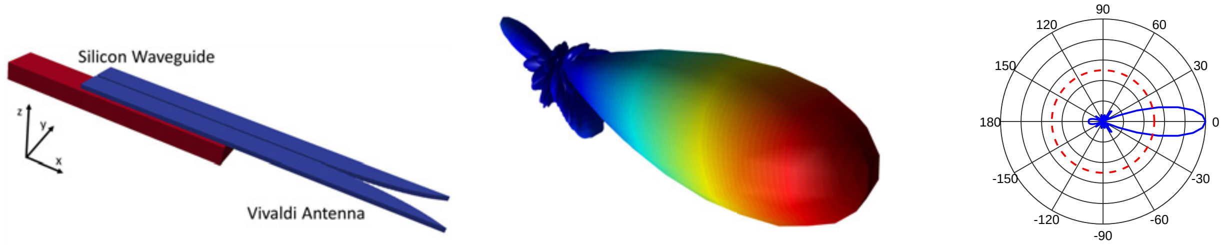

Fig. 1. Left panel: geometry of the simulated structure. Center panel: radiation surface. Right panel: radiation diagram in the horizontal (x, y) plane.

The optimization procedure for the design of this structure, and different antenna configurations, will be discussed in the final version of the work.

Investigation of a Unitary Explicit Algorithm for Electromagnetic Time Domain Simulations

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Conventional time domain methods for the simulation of photonic devices are limited by the necessity to choose small time steps because of the Courant-Friedrichs-Lewy (CFL) stability condition. A novel explicit full vectorial approach based on polynomial expansions of the time domain propagator allowing arbitrary large time steps while maintaining unitarity is presented.

Introduction: Due to the CFL stability condition, the maximum time step depends on the spatial discretization. This leads to small time steps and, therefore, to high computation times when dense spatial grids are used. Hence, alternative methods allowing larger time steps are desirable. Reasonable candidates are methods based on polynomial expansions of the time domain propagator. They allow larger time steps while the method remains fully explicit, which is desirable with regard to the possibility to employ parallel computing techniques. We examine the feasibility of these approaches for the design and analysis of photonic devices.

Summary: The investigations are based on Maxwell's equations in the time domain assuming an isotropic and lossless medium. The following equations are applied:

$$\frac{\partial \vec{\Psi}(\vec{r},t)}{\partial t} = \mathrm{H} \cdot \vec{\Psi}(\vec{r},t) \quad ; \quad \vec{\Psi}(\vec{r},t) = \begin{pmatrix} \vec{E}(\vec{r},t) \\ \vec{H}(\vec{r},t) \end{pmatrix} \quad ; \quad \mathrm{H} = \begin{pmatrix} 0 & \frac{1}{\epsilon(\vec{r})}\nabla\times \\ -\frac{1}{\mu(\vec{r})}\nabla\times & 0 \end{pmatrix} \tag{1}$$

The matrix operator H and the field vector $\vec{\Psi}(\vec{r},t)$ including the magnetic field vector $\vec{\mathrm{H}}(\vec{r},t)$ and the electric field vector $\vec{\mathrm{E}}(\vec{r},t)$ must be spatially discretized. In this case, a finite differences scheme is used but other approaches are also feasible. An expansion of the exponential operator can be applied by using Chebychev polynomials [1]. A drawback of this method is that the approximated exponential operator will not be unitary due to unavoidable approximation errors. In contrast to the exponential non unitary expansion, we extend the algorithm to obtain an enhanced and unitary time stepping scheme:

$$\vec{\Psi}(t+\Delta t) = 2 \cdot \sinh(\Delta t \cdot \mathrm{H}) \cdot \vec{\Psi}(t) + \vec{\Psi}(t-\Delta t) \tag{2}$$

Now, the Operator $\mathcal{F}(\mathrm{H}) = 2 \cdot \sinh(\Delta t \cdot \mathrm{H})$ is expanded using polynomials. Feasible methods for this task are for example the Chebychev expansion technique or the application of the Remez algorithm. By using the Von-Neumann stability analysis it can be shown that the proposed time stepping algorithm is stable independent of the used time step Δt as long as the constraint $\mathcal{F}_{appr}(\lambda) = \mathcal{F}(\lambda) + \mathcal{O}(\lambda) \leq 2$ holds.

Conclusion: An explicit time domain algorithm capable of solving the Maxwell equations is presented. The scheme is not limited to small time steps and features a unitary time propagation operator ensuring energy conservation during the simulation.

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Studies on UV electromagnetic field enhancement effects on Rh-based advanced SERS substrates

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In this contribution, results of numerical analyses of electromagnetic field enhancement effects in the ultraviolet region on several advanced Rh-based SERS substrates are presented and discussed.

Introduction

The spectroscopic technique based on surface-enhanced Raman scattering (SERS) exploits the fact, that for molecules adsorbed on noble metal nanostructures, Raman signal enhancement of several orders of magnitude can arise, mainly due to electromagnetic field localization (in hot spot regions). Prototypical materials for SERS-active substrate represent noble metals (Ag, Au). Two main requirements for high-quality SERS substrates include large enhancement factors and homogeneity of substrates [1]. Recently, Raman spectroscopy has become a promising technique, among other applications, also for the rapid identification of microbes due to its advantage of providing information on both chemical composition and the structure of biomolecules (s.c. 'whole organism fingerprint'). However, in such cases, there is an undesirable interference of the weak Raman signal with the fluorescence of biological samples which harms the applicability of the process. To avoid these problems, excitation wavelengths in the deep UV region (ideally below 250 nm) has been suggested due to complete spectral separation of Raman and fluorescence emission bands for typical biomolecules [2]. Clearly, since noble metals such as Ag or Au are inapplicable here, because of the strong interband absorption in the UV region, a demand on exploration of novel materials arises. Indeed, such noble metal with UV plasmonic effects is needed to serve as the UV complement to standard Au-based substrates. Among several possible candidates, Rhodium possesses the optimal physico-chemical properties together with extraordinary mechanical durability and corrosion resistance [3,4]. Here, the preparation procedure has been mastered, consisting of the self-assembly of SiO_2 nanospheres overdeposited with a Rh nanolayer.

Numerical studies of UV behaviour of selected advanced Rh-based SERS substrates

This contribution is focused on our recent studies on the simulations and analysis of electromagnetic field enhancement effects on Rh-based SERS-active substrates, i.e. substrates with Rh nanostructures distributed in close proximity of studied compounds. Advanced numerical electromagnetic techniques, such as rigorous 3-D finite-difference time-domain (FDTD) method, are used for reliable numerical studies, enabling via identifying correlations between the substrate performance and its morphology, to understand the undergoing physics.

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Fast Green's functions for electromagnetism on a lattice

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Owing to the isomorphism between continuous and discrete electromagnetism, the finite-difference time-domain electromagnetic field can be constructed from the discrete vector potential, i.e., from the space-time-domain scalar lattice Green's function. This is the principal building block of Green's function diakoptics.

Lattice-Green's functions

As regards the numerical modelling of optical fields in waveguides, or optical waves in more general structures, there is a multitude of dedicated modelling techniques at our disposal, e.g., quasi-analytical and asymptotic techniques, and fully numerical techniques, such as integral equation methods (global interactions via Green's functions), and finite elements, finite integration, and finite-difference techniques. Although in some situations optical wavefields can be treated in terms of linearly polarised scalar wavefields, the general case requires a vectorial full-wave electromagnetic (EM) description.

A recent addition is space-time-domain lattice Green's function diakoptics (LGFD), which combines the finite-difference time-domain (FDTD) technique with lattice Green's functions (LGFs) to capture the interactions between disjoint domains, and also accounts for radiating boundary conditions [1]. This technique had originally been envisaged for the description of optical wavefield interactions between disjoint (and possibly distant) nonlinearly, quasi-classically reacting optical media, especially in case the time-scales of EM wave physics and the excited quantum states may differ by orders of magnitude. Electromagnetically, LGFD is a hybrid mix of FDTD and discretised domain-integral-equations that relies on the availability of discrete time-domain electromagnetic LGF sequences.

Chew [2] has demonstrated that electromagnetism on a lattice (FDTD) and its continuous counterpart are isomorphic, and hence that customary continuous electromagnetic manipulations directly translate into the discrete domain. We derive the electromagnetic field from the discrete vector potential, which is constructed using a holonomic 7^{th}-order single-lattice-point recurrence scheme for scalar 3-D lattice Green's functions, first discussed in [3]. We have recently compiled a triplet of papers that describe the scalar 3-D space-time LGF sequences in detail. Through the isomorphism their properties transfer onto the electromagnetic LGF sequences reported here. Given the orientation and distance of propagation, we have determined the number of significant digits to be retained in the recurrence scheme for double-precision results, which for large distances scales slightly better than the Euler-Mascheroni constant times the maximum lateral distance to the lattice point under consideration. Possible recurrence breakdown due to a vanishing leading coefficient in the recurrence scheme can be repaired by applying the FDTD scheme on the neighbours of the pertaining lattice point.

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Rigorous semi-analytical and numerical methods for stationary solutions propagating in anisotropic nonlinear plasmonic slot waveguides

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Two distinct models are developed to investigate the transverse magnetic stationary solutions propagating in one-dimensional anisotropic nonlinear plasmonic structures made from a nonlinear metamaterial core of Kerr-type embedded between two semi-infinite metal claddings. Validation of the methods are also discussed.

Nonlinear plasmonic slot waveguides (NPSWs) have been a flourishing research topic at least since 2007 [1] due to their ability to confine the light far below the diffraction limit and due to their peculiar nonlinear effects [2, 3]. Most of the previous studies focused only on configurations with a standard nonlinear isotropic core of focusing Kerr-type. It appears that the power needed to observe the interesting nonlinear effects including the symmetry breaking of the fundamental symmetric mode is in the range of GW/m which is still too high [2, 3]. In our recent work [4], we proposed a nonlinear metamaterial core with an anisotropic effective dielectric response for the transverse magnetic (TM) polarized waves instead of the conventional isotropic one. We have found that the power needed to observe the symmetry breaking can be reduced by more than three orders of magnitude, which indicates a strong reinforcement of the spatial nonlinear effects. In this work, we discuss the two methods we developed to study light propagating in such anisotropic structure.

The first method is semi-analytical in which the anisotropic nonlinearity is treated in an approximated way. In this model, we assume that all the components of the permittivity tensor depend only on the transverse component of the electric field and the nonlinear refractive index change is small compared to the linear one. Based on the above assumptions, analytical formulas for the field profiles and the nonlinear dispersion relations in terms of the Jacobi elliptical functions are obtained. The second model is fully numerical and is based on the finite element method (FEM) to solve the stationary TM problem in nonlinear layered structures. This numerical FEM does not require any of the assumptions used in the semi-analytical method, and all the components of the effective nonlinear permittivity tensor depend on both the transverse and the longitudinal components of the electric field, moreover the nonlinear term does not need to be small, which means that it is valid beyond the weak nonlinearity regime. In order to treat the nonlinearity in the FEM, we generalize the fixed power algorithm presented in [5] and we consider a coupled nonlinear eigenvalue problem to take into account all the electric field components in the Kerr- type nonlinearity instead of the single scalar eigenvalue problem solved previously. It is worth mentioning that the first semi-analytical model provides more insight and understanding into the nature of the stationary solutions in the structure than the second, more numerical model. Nevertheless, the second model treats the nonlinearity in proper way without any assumptions on the Kerr-nonlinearity amplitude, but the field profiles are computed numerically.

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Numerical simulation of hollow waveguide arrays as polarization converting elements and experimental verification

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The Method of Lines was used to simulate the wave propagation in hollow waveguide arrays. The polarization characteristics were studied and compared with experimental results.

Introduction

Polarization conversion is achieved with birefringent structures. Hollow waveguide arrays (HWA) that are known from microwaves exhibit such a birefringent behavior. Their use as polarization elements was described in [1]. Here, we perform further numerical studies and compare them with experiments, where the structures were fabricated with electron beam lithography.

Numerical simulations and experiments

When a wave illuminates a birefringent material, the wave is split in two parts which travel with different phase velocity. At the output, the parts of the fields have a certain phase difference. As consequence, a linearly polarized input field is transformed into an elliptically polarized one. As known, such an elliptically polarized field has two axes where the fields, and with this the intensities, are maximum resp. minimum. Mathematically, a polarization is defined from these extreme values as

$$P = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}) \tag{1}$$

Special cases are the linear and circular polarization with $P = 1$ or $P = 0$.

The wave propagation in birefringent structures (here the HWA) was simulated with the Method of lines (MoL). To model polarization properties, 3D-vectorial algorithms are required. A reduction of the eigenmode system was introduced, to keep the numerical effort reasonable in the simulations. Further, matrix inversions at interfaces were computed with left eigenvectors, where these left eigenvectors are determined with simple matrix-vector products [2]. Results from simulation and from experiments are shown in Fig. 1. An HWA was illuminated by a linear polarized plane wave. By rotating this HWA (see inlay on the right) different degrees of polarization at the output were determined. It can be seen on the left of Fig. 1 that experimental and simulation results are in good agreement. By optimizing the height of the structure polarization rotation (linear to linear) or a conversion to a circularly polarized field can be achieved as shown on the right.

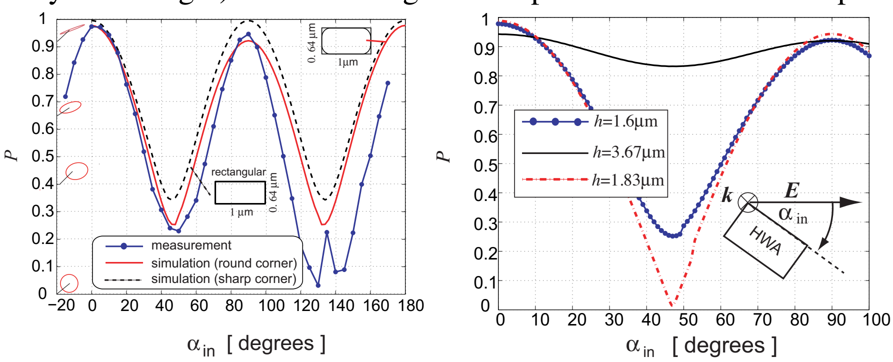

Fig. 1: Polarization P as function of angle between input field and HWA; left: comparison experiment-simulations, right: simulation results for a variation of the height of the HWA

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Novel MxN three-dimensional MMI simulation model

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Abstract

In this paper, a novel modelling method for 3D multimode interference (MMI) structures is presented. We have demonstrated the physical model and performance of a 16x16 3D MMI. The simulation results are based on self-imaging phenomena in multimode waveguides.

3D MMI simulation model

Despite the ever-increasing number of integrated on-chip elements, there is still the requirement for the miniaturization of optical devices. These two conflicting trends, as well as demand for big data transfer, force scientists to find new solutions that not only allow higher data transmission rates but also lead to more compact devices. One of the recently tested solutions is vertical integration, which allows for realization of 3D polymer structures [1]. This technique enables the creation of very complex structures that are much more compact than traditional polymer-based planar photonic components.

To interconnect different waveguide layers, a 3D MMI can be used. This work focuses on the design of an MxN 3D Multi-mode interference (MMI) simulation model. The model calculates the modes propagating in the input waveguides and overlaps them with the MMI modes. Mode propagation in the MMI is calculated using self-imaging phenomena in multimode waveguides [2]. Finally, the output waveguide mode field distribution is obtained as a sum of overlaps between all MMI modes and output waveguide modes. The accuracy of this model was proven using recently published results of a 4x4 3D polymer MMI [1]. The simulation of the model takes only several minutes. As an example, a 16x16 3D MMI has been demonstrated, as shown in Fig. 1. The presented simulations include both horizontal and vertical planes.

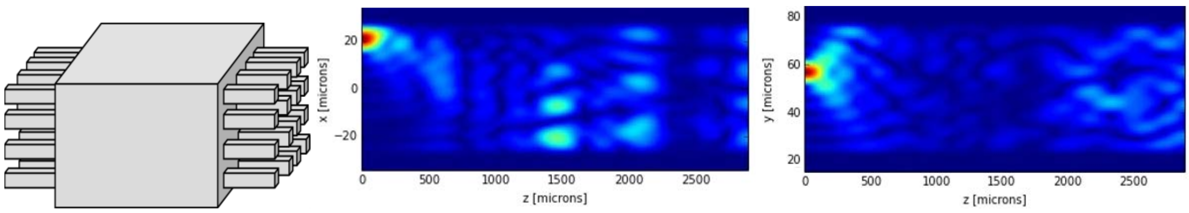

Fig. 1. Geometry and simulation results of a 3D polymer-based 16x16 MMI in the vertical and horizontal planes.

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Information content of integrable wave systems

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A theory of communications in integrable and nearly-integrable systems is developed.

Summary

In the classical theory of dynamical systems, a system is integrable if it has a sufficient number of independent 'constants of motion' K_i to permit reduction of the system to an integrable first-order equation [1]. The invariants K_i encode the initial conditions applied at initial time $t = 0$; by measuring the phase space state of the system at any time $t \neq 0$, the initial conditions can be deduced by computing the invariants K_i. For this reason, we say that the invariants K_i of a dynamical system *store information* about the initial condition. The Toda Lattice is a canonical example of an integrable dynamical system and permits an investigation of the information dynamics of integrable and of perturbed nearly-integrable dynamical systems.

Integrable wave systems are Hamiltonian dynamical systems with enough invariants to render the system soluble by quadratures. In systems of this type, the evolution variable may well be a spatial coordinate and the transverse variable may well be time.

All the equations of interest arise from compatibility conditions of a Lax pair of operators L, M, such that $\partial_t L = [M, L]$ (for dynamical systems) or $\partial_z L = [M, L]$ (for propagating wave systems). The Lax operators are actions on some Hilbert space, and the eigenvalues of the operator L are conserved in the evolution. The integral invariants are then the functions $K_i = \mathrm{tr}\{L^i\} = \sum_j \lambda_j^i$, and the Lax eigenvalues are the action variables of the action-angle pair of canonical coordinates.

Once the eigenvalues are determined for the Lax operator L, the entire evolution of the system is essentially solved. For a dynamical system of N particles evolving in time t the Lax operator L is a $N \times N$ matrix whose eigenvalues $\{\lambda_i : j = 1, \ldots, N\}$ encode the initial conditions. For a wave system propagating along the spatial coordinate z, the Lax operator L is usually a linear differential operator in time t, whose eigenvalues (discrete and continuous) encode the initial ($z = 0$) values of the wave.

In 1993 Hasegawa and Nyu [2] proposed that Lax eigenvalues of the Nonlinear Schrodinger equation might be exploited as carriers of information. Recently an experimental system [3], involving transmission over 1500 km of optical fibre, has demonstrated 'conservation of eigenvalues' to a high precision. We speculate further on the encoding and decoding devices that might enhance the feasibility of this kind of 'eigenvalue communication'. The key points of this approach are: (i) to exhibit the physical equations as a Lax pair perturbed in some way; (ii) to specify physical devices by which eigenvalues of the underlying Lax pair can be encoded and decoded; (iii) to analyse the way in which the ideal information transfer of the underlying integrable system is degraded by near-integrable perturbations and the introduction of noise in the encoding-decoding process [4].

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Spectral engineering of the transmission characteristics of racetrack resonators

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We report the study of the transmission characteristics of a vertically-coupled racetrack resonator as a function of the design of its constituting waveguides. We show that the use of asymmetric couplers can lead to quasi-critical coupling over a large spectral range and thus be useful for Kerr frequency comb generation.

Introduction

Integrated whispering gallery mode resonators constitute a family of compact devices which has been shown to be attractive to perform selective filtering, low-threshold emission or nonlinear conversion functions [1]. In the latter case, and for Kerr frequency comb generation in particular, the performance is controlled by the ability to achieve critical coupling over a wide spectral range. In this paper, we study the influence of the coupler design on the spectral response of vertically-coupled racetrack resonators and draw out design rules to achieve wideband critical coupling.

Methodology and results

The spectral response of the resonators under study (see inset of Fig. 1.) is analysed using a coupled-mode theory approach. Following references [2-3], the resonator transmission characteristics consists of a set of Lorentzian-shaped dips whose lower-bound amplitude is given by

$$T_{res-} = \frac{|t|^2+\alpha^2-2\alpha|t|}{1+|t|^2\alpha^2-2\alpha|t|} = \frac{(\alpha-|t|)^2}{(1-\alpha|t|)^2} \qquad (1)$$

where $t=A_1(L_c)/A_1(0)$ is the field transmission coefficient of the coupler access waveguide and α is the single-pass loss coefficient of the resonator.

Fig. 1. illustrates that adjusting the coupler length while keeping unchanged the resonator loss spectrum significantly modifies the critical coupling (T_{res-}~0 or $|t|\sim\alpha$) bandwidth. The parametric study reveals that the widest bandwidth is obtained with an asymmetric coupler whose length is close to be the coupler half beat length ($L_\pi/2$). Physically, as it will be detailed at the meeting, this optimum arises because asymmetric couplers permit to, not only tailor the wavelength dependence of L_π, but also control the influence of the latter parameter through the adjustment of the maximum coupled power fraction, thereby enabling $|t(\lambda)|$ to mimic the weak spectral variations of the resonator loss.

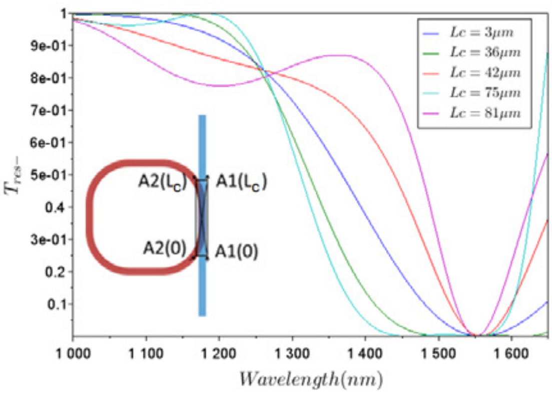

Fig 1: Calculated resonance-dip envelops inset: Studied resonator geometry

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Modelisation of zero-contrast grating filters for pixelated applications in the mid-IR range

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In this paper, we report a way to adapt zero-contrast grating (ZCG) filters [1] to mid-IR multi-spectral applications by increasing their bandwidth and angular tolerance by a decade or more. For a central wavelength of 4.95µm, we achieve a filter's bandwidth of 38nm, compatible with 120µm pixel-sizes.

Introduction

It has been shown recently that ZCGs can be used to implement bandpass transmission filters [1]. They consist of a partially-etched high-index waveguide on a low-index substrate. A major advantage of such filters is that their central wavelength can be adjusted simply by modifying the period of the grating, not the thickness of the system. However these filters have a low angular tolerance which limits the smallest possible pixel size, and their bandwidth is only of few nm which restricts too much the incident flux. In this paper we report a simple and efficient method to design 1D narrowband filters as well as the first use of a doubly-corrugated grating in order to increase both the bandwidth and angular tolerance of a ZCG. The design method relies on both analytical and empirical relations as well as little numerical optimization performed using Rigorous Couped Wave Analysis (RCWA).

Results

Its application allowed us to design a narrowband ZCG using germanium as high-index material and calcium fluoride as substrate with a maximum transmission of almost 100% at 4.952µm, a full width at half-maximum (FWHM) of 1.7nm, and an angular tolerance of 0.27°.
We found that the addition of a small secondary corrugation in the grating allows us to widen the bandwidth of the filter. We relate this effect to a modification in the grating coefficients, which affects the coupling between the waveguide modes and the incident electric field. The FWHM is controlled by the additional corrugation size. We designed such a device having a FWHM of 38.6nm and an angular tolerance of 3.1°, which represents more than a 20 and 10 fold increase respectively in the FWHM and angular tolerance compared to the narrowband design. Within the Gaussian beam model, we extract a typical pixel size of around 120µm for the doubly-corrugated device, thus more than a decade reduction as compared to the narrowband design. We have also verified that the wideband device's wavelength can be tuned along with the period of the grating. These structures take into account the necessary requirements for production using photolithography and etching processes.

Conclusion

We have introduced a pixelization-compatible design for mid-IR bandpass transmission filters that would compare favourably with thin film designs as well as existing ZCG-based concepts by increasing both bandwidth and angular tolerance of a simple ZCG.

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Bidirectional modelling of fiber Bragg gratings

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Modelling of fiber Bragg gratings (FBG) presents a challenge due to periodic reflections involved in the propagation. Although methods for bidirectional propagation for planar structures have been developed, dealing with cylindrical or two-dimensional structure still presents difficulty due to excessive computational effort. We discuss two approaches to propagation in periodic fibers, FBGs.

Summary

Fiber Bragg gratings involve index changes at regular length intervals of an optical fiber. Typically, an FBG would consist of a plain fiber section followed by a section where the index has been changed in some way. It can generally be assumed that the entire structure remains cylindrically symmetric.

In modelling propagation in an FBG, the most important aspect is to account for reflections accurately and hence, it is imperative that the propagation solver be bidirectional. We have earlier developed a split step non-paraxial (SSNP) method [1] which is bidirectional and has been used for planar structures [2]. We have also developed earlier the collocation method in which direct solution of the wave equation can be implemented making it bidirectional and non-paraxial [3]. Combining these two methods we have developed a transfer matrix approach to propagation through an FBG as

$$\begin{pmatrix} E_+ \\ E_- \end{pmatrix}_{z=0} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} E_+ \\ E_- \end{pmatrix}_{z=L}$$

where + and – refer to forward and backward propagating fields. By putting the backward propagating field at $z = L$, we can obtain other fields in term of the incident field. The advantage of the SSNP and the collocation method is that one can obtain the transfer matrix independent of the propagating field. Thus we obtain the transfer matrix, **T**, as

$$\mathbf{T} = \mathbf{V}\left[\mathbf{P}_0(l_1)\mathbf{P}_1(l_2)\right]^m \mathbf{V}^{-1}$$

where $\mathbf{P}_0(l_1)$ is the propagation through uniform fiber section of length l_1 obtained using the collocation method, $\mathbf{P}_1(l_2)$ is the propagation through section of length l_2 of the fiber where the index (could be *z*-dependent) has been changed, **V** converts the forward and backward propagating fields to the field and its derivative at a given *z* and *m* is the number of periods in the FBG. The results obtained using the above formalism will be presented at the Workshop.

We will also examine the use of our earlier developed method to model an optical fiber as an equivalent planar waveguide [4] for modelling propagation in FBGs and employ the collocation method and the SSNP for the planar structure [2].

This work was financially supported (for R.K.) by the University Grant Commission (UGC) Govt. of India.

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Extremely enhanced figure of merit in nonlinear plasmonic waveguides in the C-band using metamaterials and a nonlinear active medium

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We propose new nonlinear plasmonic slot waveguide NPW using available materials that achieves the highest reported FOM among both plasmonic and all-dielectric nonlinear waveguides. Our new NPW can be a building block for ultra-compact photonic devices working in the telecommunication C-band.

Nonlinear plasmonic waveguides (NPWs) have attracted consideration in the last decade due to the strong light confinement, their peculiar nonlinear effects, and their small footprint [1]. Nevertheless, no clear enhancement of the nonlinear figure of merit (FOM) compared with all-dielectric waveguides has been observed yet. In this work, we propose new NPWs based on an active semiconductor indium gallium arsenide phosphide (InGaAsP) as a nonlinear core material and metamaterial claddings with an isotropic dielectric response for the transverse magnetic polarized (TM) waves. Fig. 1(a) illus-

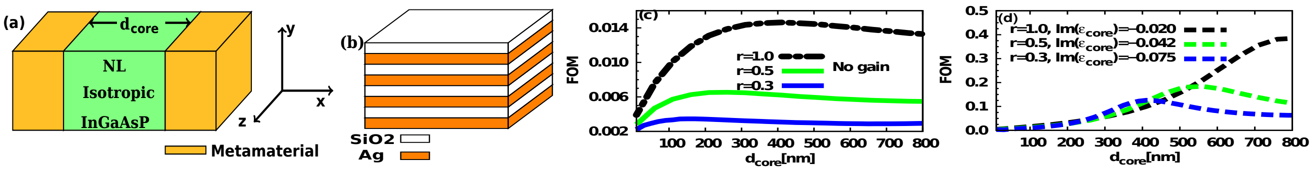

Fig. 1. (a-b): Symmetric NPW with its metamaterial cladding. (c-d) FOM as a function of the core thickness d_{core} for three different metal ratios in the metamaterial. (c) without gain and (d) with gain. The FOM is computed using the formula provided in Ref. [2].

trates the plasmonic waveguide configuration under investigation. The metamaterial cladding made of a simple stack of silver and silica layers (see Fig. 1(b)) has an isotropic dielectric response for TM waves. In Fig. 1(c), we demonstrate the influence of the metamaterial on the FOM by changing the ratio of Ag in the stack (denoted by r). For small r, the absolute value of the cladding permittivity decreases, thus increasing the permittivity contrast between the core and the claddings which induces a tight confinement and a small effective area. Nevertheless, large parts of the field will be located in the lossy claddings. Therefore, due to the trade-off between the confinement and the losses, we have found that decreasing the r parameter results in a decrease of the FOM as shown in Fig. 1(c). Now, since InGaAsP can be pumped to act as a gain medium [3] around the telecommunication wavelength, we have observed a huge enhancement of the FOM for the tested r values (see Fig. 1(d)). Furthermore, the maximum FOM is shifted towards small core thicknesses with the decrease of r. Even if, the maximum of the FOM is decreasing, it is still enhanced by more than 100 times compared with its corresponding value without gain (see the blue curves in Figs. 1(c), and 1(d)). It is worth noting that all the gain values used in our study are valid for InGaAsP [3] and that the obtained FOM are 10 times higher than the theoretical FOM computed for the best all dielectric nonlinear waveguides.

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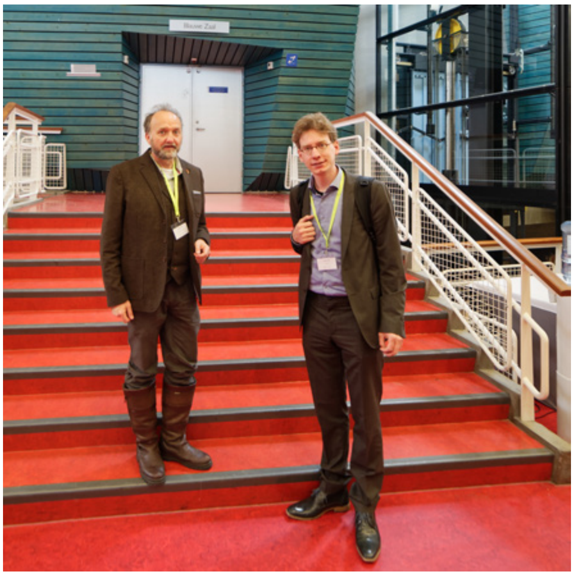
Photos and Artwork

OWTNM 2017 group photo made at the start of the poster session.

Left: local organisers Bastiaan P. de Hon (Electromagnetics Group) and Sander J. Floris (CommScope).
Right: Chigo M. Okonkwo (Electro-Optics Group) gives a tour of the experimental optics facilities.

Animated OWTNM 2017 Logo by S.J. Floris and B.P. de Hon. An encircled flux compliant source generates four million rays. One million rays remain after filtering using the OWTNM mask. Standard multi-mode fiber with a 50 mum core diameter at 850 nm wavelength. The propagation distance is $1.15\,\mathrm{mm}$.
(Click on image to start. Some Pdf viewers do not support this kind of animation.)

Acknowledgments

We would like to acknowledge the generous financial contributions from the sponsors of the co-located ECIO conference and OWTNM workshop, in particular we would like to thank

AMO GmbH, Aachen, Germany
CommScope, Utrecht, the Netherlands
EPIC – European Photonics Industry Consortium, Eindhoven, the Netherlands
JePPIX, Eindhoven, the Netherlands
Light Tec SARL, Hyères, France
NKT Photonics, Birkerød, Denmark
OpTek Systems, UK & Europe, Abingdon, United Kingdom
PhoeniX Software, Enschede, the Netherlands
Photon Design, Oxford, United Kingdom
Raith GmbH, Dortmund, Germany
SENTECH Instruments GmbH, Berlin, Germany
SMART Photonics, Eindhoven, the Netherlands
VLC Photonics, Valencia, Spain
VPIphotonics™ GmbH, Berlin, Germany

Further, we would like to express our appreciation regarding the services delivered by Jakajima. Finally, we would like to thank Manfred Hammer and Trevor Benson for their sage advice, and Jolanda Levering and Suzanne Kuijlaars for altruistically organising the catering and our space within the venue.