Design and Analysis of Even-Positioned Cavity-Based Optical Amplification Device in Dielectric Metasurface

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***Abstract* — Recently, the development in the field of optical technology is exemplary, specifically relating to the design of the components necessary for optical integrated circuits. This research work investigates optical amplification action in a 2D Photonic Crystals (PhCs) structure with variable radius even-positioned PhC-cavity within its lattice. Two optical signals are used, first acting as data signals coupled into the optical structure using the phenomenon of the Guided-mode-resonances (GMR) and the second one as a pump signal index-guided into the optical structure. The pump signal is used to amplify the data signal and the PhC-cavity is used for spectral tuning of the device operating in near-infrared (NIR) range. The dielectric structure consists of an optical waveguide packed in between the substrate and a cladding layer. The design and analysis of the proposed device is performed in a Finite-Difference-Time-Domain (FDTD) based open-source software package. The investigated results present optical amplification for the radius of the PhC-cavity greater than the standard radius of the PhC-elements used in the structure. Moreover, as a concluded fact, PhC-cavity nearer to the symmetric point of the optical structure will greatly influence the amplification and tuning of the GMR modes. Therefore, the investigated device can be used in applications relating to optical transistors, filters, and integrated circuits.**

Keywords — Optical amplification, Dielectric Metasurface, Photonic Crystal Cavity, Guided Mode Resonance, Finite-difference Time-domain

I. INTRODUCTION

The past decade has witnessed an increase in the research relating to the field of the optical-technology in terms of optical sensors, filters, switching devices, and their usage in optical integrated circuits [1,2]. Moreover, the electronic-technology is at its peak and meeting the demands of the modern world especially in the fields of image processing, artificial intelligence, security, and biomedical systems [3]. However, at the same pace, the number of transistors, cost, and processing time of these systems increase exponentially making the electronic technology reaching to its break-point. Therefore, an alternative to prevailing technology according to the view of the researchers is optical technology with extensive research in the field to design, develop and implement the integrated-optical components and efficiently conclude it in densely populated optical integrated circuits [4]. However, as the optical-technology is still in its infancy stage and the limitations of the existing systems abstain from its existence in the real world.

PhCs, are the nanostructures capable of controlling the light at wavelength scale. They are present in nature [5] and can be designed and implemented artificially as well according to the requirements of specific devices [6]. This research investigates the design of the optical switch based on a dielectric PhC-based structure targeting the 1.55μm NIR range. Likewise, consists of an optical waveguide with a refractive index of $n_w = 2.2$ in between the layers of the substrate and cladding having a refractive index of $n_s = 1.5$ using cylindrical PhC-elements with radius 0.207a, where ‘a’ is the lattice constant and equal to 1μm. Moreover, all the designing parameters of the structure are expressed in terms of ‘a’ so that the design can be rescaled to any wavelength range . Similarly, the thickess of the waveguide and cladding layer are choosen as 0.44a and 0.68a respectively, with value of the field decay monitoring point as $1e^{-3}$. Hence, the optical-amplification action is achieved using two optical signals i.e., data signal and pump signal with comparative response of the two even-positioned varying radius PhC-cavities.

II. METHODOLOGY

The simulation of the structure is performed using an open-source software package known as MIT Electromagnetic Equation Propagation (MEEP) [7]. FDTD technique works by dividing the infinite structure into small grids called YEE grids. Later on, the response of the structure is studied using the leap-frog method, by calculating the respective Electric field ‘E’ and Magnetic field ‘B’ on the nodes using Maxwell’s equations. The differential form of Maxwell equations are converted into finite differences which enable the calculation of EM field on this nodes. Similarly, three fundamentals are taken into account for the said investigation i.e., initial conditions, permittivity distribution, and boundary condition. The basic model used in this research is reflected in Fig. 1 comprising of data signal implemented above the structure, a pump signal on the left side. Two nano-cavities are placed at even positions as depicted in the figure. The 2D simulation domain of the structure comprises of grid of size 30a(x) × 0a(y) ×11a(z) including a wall of 3.0a PML boundary condition, terminating the structure in x and z-dimensions as indicated by red-square.. Similarly, to produce smooth, recognizable and best fit results of the structures, the smoothing factor (grid resolution) is used, equalling to 1/resolution. Therefore, the resolution taken for this research is selected to be 20, equaling the smoothing factor to 0.05, which is smaller than wavelength/30, which equals to 0.052.

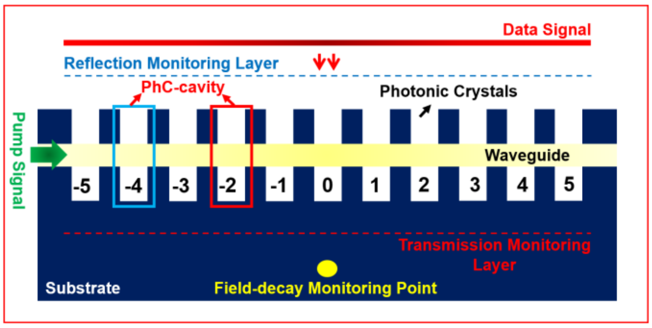

Fig. 1. Simulation model of optical amplifier with two nano-cativites in the PhC structure with indication of data and pump signal and reflection and transmission moitoring layers above and below the structure respectively, bounded by PML boundary condition

III. RESULTS

The results of the research are divided into sections i.e., two varying radius cavities are simulated using data signal separately to investigate their effects on the GMR modes in terms of shifting as shown in Fig. 2.

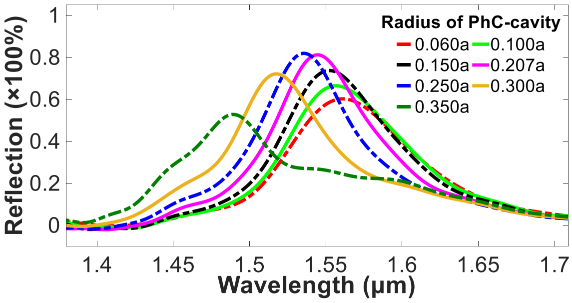

Fig. 2. Reflection spectra showing the change in reflection peak and spectral location of resonant modes for 11 PhC-elements-based structure by changing the radius of the PhC-cavity in the range 0.06a-0350a positioned at -2 only, using data signal with change in wavelength from 1.561 μm to 1.489 μm

This cavity will break the lattice of the PhCs and will help to shift the dips of the reflection spectrums accordingly larger wavelength towards shorter wavelengths as the radius of the cavity tends to increase and vice versa. Secondly, the arrangements are simulated using the data signal (solid) and pump signal (dotted) simultaneously to see the effects of the optical amplification as shown in Fig. 3. Moreover, the following radius of the PhC-cavity i.e., 0.150a, 0.207a, and 0.250a are used. Thus, the implementation of the pump signal helps to amplify or de-amplify the given data signal.

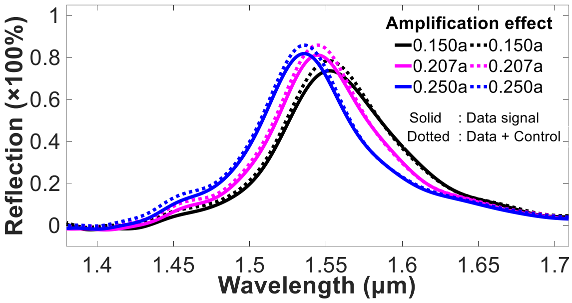

Fig. 3. Variation in the reflection peaks to show the phenomena of optical amplification using pump signal (dotted) along the data signal (solid) and radius of PhC-cavity positioned at -2 only as 0.150a, 0.207a and 0.250a respectively with change in wavelength from 1.553 μm to 1.536 μm

IV. CONCLUSION

In this paper, a comparative study of the PhC-based optical switch is investigated using two even-positioned cavities within the lattice of the PhC structure. Moreover, the radius of these cavities is varied and concluded for a structure to observe the phenomenon of PhC-based optical switching in terms of increase in confinement of energy and amplification percentage i.e.,5%, decrease in linewidth i.e., 0.004a and increase in quality factor of the GMR-modes i.e., 1.2 for a PhC-cavity of radius 0.207a positioned at -2.

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