9:05am - 9:20am
THA4

A versatile all-optical modulator based on nonlinear Mach-Zehnder interferometers

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Introduction

High bit rate communication systems of the future will demand ultrafast devices for routing signals, controlling polarisation, converting wavelengths and performing logical functions. Without doubt it is a great benefit when all this can be done completely in the optical domain. In this paper we describe a device based on a Nonlinear Mach-Zehnder interferometer (NMI) which exploits cross-phase modulation (XPM) of two co-propagating modes in bimodal branches. This is in contrast to the device as introduced in [1] which exploits XPM of orthogonally polarised modes of monomode waveguides. The advantage of the new concept is the fact that the device becomes polarisation independent while keeping phase insensitive by using different propagation constants of the modes of the bimodal branches.

Basic operation

A schematic lay-out of the proposed Nonlinear Mach-Zehnder interferometer is shown in Figure 1. The structure is assumed to consist of materials with Kerr nonlinearities. It has three inputs; the middle one is used for insertion of a probe beam (P_p), the two outer waveguides for insertion of control beams (P_c^1 and P_c^2). The probe beam is equally divided over two branches by the central Y-junction and each of them is also the wider input of an asymmetrical Y-junction. When carefully designed [2] these latter Y-junctions cause the modes from the wider input channel and the smaller input channel to convert adiabatically into the fundamental and first order modes respectively of the bimodal waveguides 1 and 2. So when both probe and control power are inputted as fundamental and first order modes they will co-propagate through the bimodal sections and induce mutual phase changes by XPM. At the end of the branches the fundamental mode (the probe) and the first order mode (the control) are separated with the same asymmetrical Y-junctions, now used in reversed direction since they act as mode-splitters in this direction. The fundamental modes propagate into the centre Y-junction at the output where they will recombine. The in-phase parts will add up to form the fundamental mode of the output. The transmission of the probe can be given by:

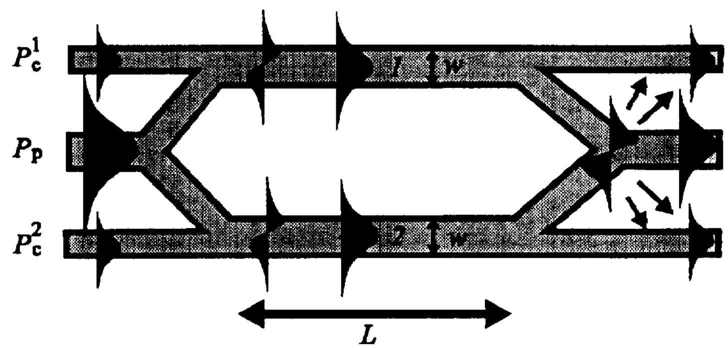

Figure 1: Schematic lay-out of the proposed NMI.

$$\frac{P_{out}}{P_{in}} = \cos^2(\Delta\phi/2) \qquad (1)$$

where $\Delta\phi$ is the phase difference of the two fundamental modes at the end of the branches. The phase of the fundamental modes at the end of the branches is determined by the propagation constant and the self-phase modulation (SPM) of the probe mode and the XPM by the control. Using the expressions for the nonlinear polarisation and restricting the terms to those at $\omega=\omega_0$ (the frequency of the light used) which are independent of the propagation co-ordinate, the nonlinear induced phase change of the probe modes is given by [3]:

$$\Delta\phi_p^i(L,P_p,P_c^i) = (Q_{pp}^i\frac{P_p}{2} + 2Q_{pc}^iP_c^i)L \qquad \{i=1,2\} \tag{2}$$

where i denotes the branch and L is the length of the branches. The nonlinear coupling coefficients are given by the well-known overlap integrals:

$$Q_{\mu\nu}^i = \frac{\omega\varepsilon_0}{2}\int_{x=-\infty}^{\infty}\int_{y=-\infty}^{\infty} n_0 n_{2e}|E_\mu^i(x,y)|^2|E_\nu^i(x,y)|^2 dxdy \qquad \{\nu,\mu = p,c\} \tag{3}$$

where E_ν^i and E_μ^i denote the normalised fields of modes ν and μ in branch i and where n_{2e} is the nonlinear Kerr-index. Assuming that the branches are identical the phase difference at the output is given by:

$$\Delta\phi = \Delta\phi_p^1 - \Delta\phi_p^2 = 2Q_{ps}(P_c^1 - P_c^2)L \tag{4}$$

For the case of one input (i.e. say P_c^2=0) the switching power is found for $\Delta\phi=\pi$:

$$P_s = \frac{\pi}{2Q_{pc}L} \tag{5}$$

It is worthwhile remarking that for isotropic waveguide structures the field profiles are not strongly depending on the polarisation. There is, however, in general a dependence of n_{2e} on the polarisation direction thus making the nonlinear coupling coefficients polarisation sensitive. Nevertheless, since the switching curves are rather flat around $P=P_s$, according to (1) more than 93% switching can be obtained by taking P_s as the average value of the P_s-values for cross- and equi-polarised beams. Furthermore by avoiding working in the proximity of any resonance's, the dispersion of n_{2e} will be relative small thus making the device operate at a range of wavelengths even when using different probe and control wavelengths. Finally $\Delta\phi$ is independent of P_p implying that, according to this first order analysis, any probe power can be switched by the controls. Hence, the device enables modulation, amplification and wavelength and polarisation conversion at one time.

Numerical results

As an example of the proposed concept we numerically investigated a possible implementation of the structure in $Al_xGa_{1-x}As$ technology. The waveguide geometry comprises a 40% Al substrate, a 1.0 µm thick 18% Al film layer and a 1.5 µm thick 30% Al cladding layer, etched down to 0.35 µm in the regions adjacent to the waveguides. Taking these concentrations the bandgap energy will be a little higher than 2 times the photon energy for 1.55 µm wavelength thus virtually eliminating two-photon absorption [4]. Refractive indices and nonlinearities were calculated using expressions as given in [5]. The mode profiles of the waveguides were analysed by means of a Finite Difference scheme [6]. Results of these calculations were compared to those of Nonlinear Effective Index calculations [7] showing very good similarity with regard to the field profiles and the nonlinear coupling coefficients. This implies that further analysis of the device lay-out could be pursued by applying two dimensional BPM calculations.

The Y-junctions were optimised using simple approximate expressions [8]. It was found that 0.15 degrees branching angles in combination with 2 and 2.5 μm wide input waveguides gives a Mode Conversion Factor of ≈ 2. This on its turn should yield a mode selectivity of ≈26 dB which indeed was nearly (24 dB) observed in Enhanced Finite Difference Beam Propagation (EFDBPM) calculations [9]. A branch to branch separation of 20 μm was found to give sufficient decoupling (-60 dB) of the modes in the two branches of the NMI. Aiming at a total device length of 2.5 cm and reserving 4 mm for the centre output waveguide in order to allow the radiation modes to spread out in the environment, a branch length of 1.5 cm resulted. The CW performance of the described structure was analysed by means of EFDBPM calculation. P_p was taken to be fixed at 200 W whereas P_c^1 was varied between 0 and 100 W. Figure 2 top shows the calculated transmission curve for P_p versus P_c^1. The transmission clearly shows a strong modulation due to the weaker signal beam leading to an almost absence of power (0.02 %) in the output for P_c^1 =22 W. This is illustrated in the middle part of Figure 2 which shows $|E(x,z)|$ as obtained by EFDBPM. Finally we studied the modulation of a 200 fs long probe pulse (P_{peak} = 1 W) by a 1 ps long signal pulse (P_{peak} = 45 W) by means of a split-step Fourier method [10]. Figure 2, bottom, shows that the probe pulse is fairly equally modulated over the complete length of the pulse without any substantial pulse break-up

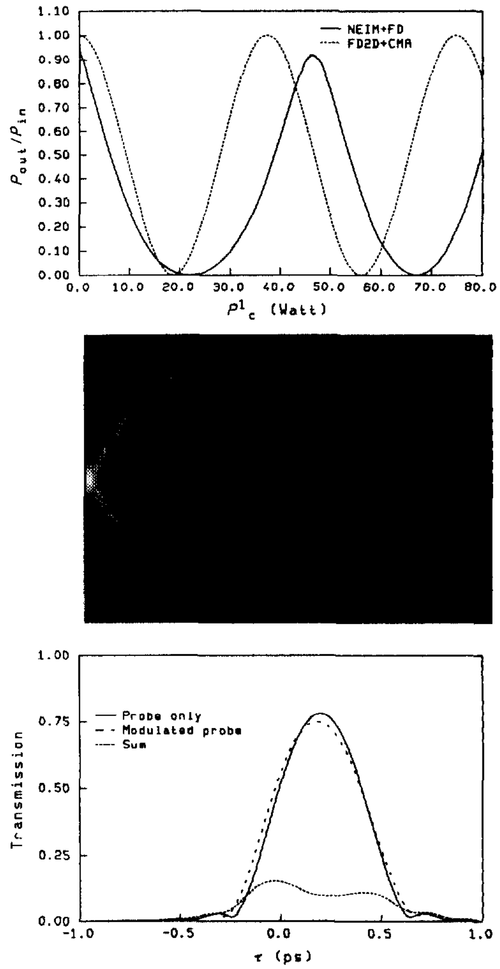

Figure 2: Top: Transmission of a 200 W probe beam versus input signal. Middle: modulus of the electric field (P_p=200 W, P_c^1 = 22 W). Bottom: calculated pulses.

Acknowledgement

The research of Gijs Krijnen has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences.

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