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MODEL OF A NONLINEAR MACH-ZEHNDER INTERFEROMETER IN GALLIUM ARSENIDE

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Resume - Nous avons utilisé un modèle réaliste des nonlinairités optiques pour calculer la réponse d'un interferomètre nonlinéaire de Mach-Zehnder fabriqué dans une structure en guide d'onde de AlGaAs/GaAs. Le modèle inclut la dépendence de l'indice de réfraction complexe par rapport à la densité de charges, ainsi que la diffusion latérale des charges dans les deux bras du guide d'onde.

Abstract - We have calculated the response of a nonlinear Mach-Zehnder interferometer fabricated in an AlGaAs/GaAs waveguide structure using a realistic model for the optical nonlinearities. The model takes into account carrier density-dependent index of refraction and absorption and lateral carrier diffusion in each of the two channel waveguides.

INTRODUCTION

All-optical nonlinear waveguide devices have potential uses in the areas of guided-wave optics and optical communications. The success of electro-optically controlled waveguide devices and the growing interest in nonlinear optical interactions in waveguides lead naturally to the concept of an all-optical nonlinear Mach-Zehnder interferometer (NLMZ). In this device, a single channel waveguide is split into two channel waveguides which, after a given distance, merge again into a single channel waveguide. The output of the device obtains therefore either a minimum or maximum value depending on the net phase difference between the two interfering modes. The source of the optically induced phase difference can derive, for example, from an unequal-arm-length configuration, as shown in Figure 1a, which was investigated by Kawaguchi using Kerr-effect media. A different geometry, which is based on an equal-arm-length concept and shown in Figure 1b, requires different optical power levels in each of the arms. Such a design, demonstrated with lithium niobate, can allow for multiple inputs for both signal and control beams. For practical applications, the nonlinear phase difference across the NLMZ should be on the order of π. The need to obtain large phase shifts with reasonable power levels and device lengths has shifted the emphasis to semiconductor materials that have large nonthermal optical nonlinearities. The penalty associated with these large nonlinearities derives from the requirement that a finite fraction of the optical field be absorbed, since the nonlinearity originates from resonant electronic transitions in the semiconductor. Consequently, one is faced with a trade-off between the value of the nonlinearity and that of the net total absorption. Rather than use a simplified model for the nonlinearity, such as the Kerr-effect or the two-level system, we employ a realistic theory that incorporates the many effects associated with the generation of an electron-hole plasma in a semiconductor. We present in this paper a design that utilizes the plasma theory for the equal- and unequal-arm-length NLMZ interferometers fabricated in bulk gallium arsenide (GaAs). Of the potential direct-gap semiconductors, bulk gallium arsenide possesses a large optical nonlinearity, a near-infrared band edge compatible with optical communications, and large electro-optic properties suitable for hybrid devices.

Figure 1. Two NLMZ geometries. (a) The unequal-arm-length NLMZ where the input signal is the source of the nonlinearity and (b) the equal-arm-length NLMZ where the controls C are the source of the nonlinearity. The input S is the constant signal input modulated by the control. The arrows and dots indicate the input polarization and PS is an output polarizer.
THEORY

Our theoretical approach assumes that the perturbation of the optical mode in each of the channel waveguides arises from the nonlinear optical properties of the material. The optical mode of a waveguide is said to be only slightly perturbed when the absorption and the nonlinear index changes are small over the propagation distance of several wavelengths and, consequently, the transverse-mode profile in the waveguide remains virtually unchanged. The net absorption, however, and the nonlinear index change along the device substantially alter the amplitude and phase of the mode. This analysis applies for both the equal- and unequal-arm-length devices, and by making a few simple assumptions, the effects of carrier diffusion can be included in the theory. The analysis of the NLMZ starts where the single waveguide splits into two waveguides. Perturbation theory allows the longitudinal and transverse responses of the modes in each waveguide to be treated separately. One can, therefore, model the longitudinal behavior of the NLMZ by a set of first-order differential equations derived from the wave equation and the modal properties of the waveguides [6]:

\[
\frac{\partial a_i}{\partial z} = -a_i \alpha_i - i \Delta \beta_{ii} a_i ,
\]

[1]

\[
\frac{\partial a_2}{\partial z} = -a_2 \alpha_2 - i \Delta \beta_{22} a_2 ,
\]

[2]

where \( z \) is along the propagation direction. Here, \( a_i \) and \( a_2 \) are the amplitudes of the guided modes in guides 1 and 2, respectively, and \( \alpha_i \) and \( \alpha_2 \) are the amplitude absorption coefficients of the respective guides. \( \Delta \beta_{ii} (i = 1,2) \) is the nonlinear perturbation to the propagation constant in each waveguide given by

\[
\Delta \beta_{ii} = \frac{k_c e_i}{2P_i} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_{i}^* \Delta n_{ni}(N)E_{i} dx dy .
\]

[3]

Here, \( E_i \) is the transverse electric-field profile in guide \( i \), \( \Delta n_{ni}(N) \) is the nonlinear change to the squared index distribution caused by the local charge-carrier density, \( N = N(x,y) \), in guide \( i \), and \( P_i \) is the total power carried by the mode in guide \( i \). Also, \( k_o = 2\pi/\lambda \) is the free-space propagation constant, \( \lambda \) is the wavelength in vacuum, and \( c \) is the speed of light in vacuum. The derivation of Eqs. [1] and [2] assumed that the coefficients \( \alpha_i, \alpha_2, \Delta \beta_{ii}, \) and \( \Delta \beta_{22} \) do not change along the propagation distance and are, therefore, analytic solutions to each differential equation. Generally, the coefficients are functions of \( z \), but one assumes that the changes are small over the propagation distance of several wavelengths and, consequently, the differential equations are still suitable for representing the mode amplitude in each waveguide. Equations [1] and [2] are numerically integrated while updating the coefficients at each step, and the normalized mode amplitudes, \( a_i \) and \( a_2 \), are determined as the two waveguides recombine into a single waveguide. The final step in the calculation is to interfere the fields at the output of the NLMZ. For the unequal-arm-length NLMZ, the electric field of the guided mode, when the two waveguides recombine, is expressed by

\[
E_{t}(x,y,z,t) = E_{1}(x,y,z_1,t) + E_{2}(x,y,z_2,t),
\]

[4]

where the electric fields in each waveguide are given by

\[
E_{1}(x,y,z_1,t) = a_1(z_1)E_{1}(x,y)\exp[i(\omega t - \beta_1 z_1)] ,
\]

[5]

\[
E_{2}(x,y,z_2,t) = a_2(z_2)E_{2}(x,y)\exp[i(\omega t - \beta_2 z_2)] .
\]

[6]

The symbols \( z_1 \) and \( z_2 \) refer to the respective waveguides and demonstrate that the fields have propagated unequal lengths before they were recombined at some value of \( z \). The intensity carried by a mode is proportional to the squared electric field and, for identical guides with equal input powers, can be written as

\[
\frac{I_{t}}{I_{i}} = |a_1(z_1)|^2 + |a_2(z_2)|^2 + a_1(z_1)a_2^*(z_2) + a_2(z_2)a_1^*(z_1) ,
\]

[7]

where \( I_{i} \) is the input intensity. Although these equations assume interfering plane waves, they adequately describe the output of the NLMZ and keep the analysis simple. An equal-arm-length NLMZ may have multiple inputs for controlling the power in each arm. The signals and controls are predominantly polarized orthogonal to each other. The control modes would therefore provide nonlinear changes in the index of refraction and consequently modify the phase of the signal modes in their respective waveguides, without interfering with the output signal. The control portion of the output can be blocked by a crossed polarizer while the signal portion is allowed to pass. Equations [1] through [7] reduce to the case of the equal-arm-length NLMZ by equating \( z_1 \) and \( z_2 \) and by taking into account that each waveguide may support both a signal and a control mode. The NLMZ is modeled as a rib waveguide fabricated in GaAs using the effective index method and has a bulk GaAs core with an air cover.
medium and AlGaAs substrate. For a well-guided mode, an equivalent channel waveguide with well-known modal properties can be derived and used to evaluate the nonlinear changes in the propagation constant, and the waveguide structures support only fundamental modes. The local nonlinear changes in index and absorption for the GaAs core are calculated from the local carrier density using the plasma theory. The nonlinearities are limited to the bulk GaAs since the band edge of the AlGaAs substrate is at higher energies and its nonlinear absorption and index changes are therefore negligible. The local carrier density is derived from the mode intensity profile by using the transverse diffusion equation. However, if one assumes that the carrier diffusion length is larger than the width of the mode, the resulting carrier-density profile becomes uniform across the mode, which simplifies the calculation by allowing one to use an average carrier density across the mode. The material parameters used to generate Figs. 2 and 3 are: wavelength, 0.9 µm; GaAs core index, 3.597; AlGaAs substrate index, 3.518; guide height, 0.5 µm; guide width, 2.0 µm; and diffusion length, 5 µm. Parameters relevant to the plasma theory can be found in Ref. [9]. Figure 2 illustrates the output power of the unequal-arm-length NLMZ as a function of input power. The results are for the rib-waveguide structure and illustrate the output behavior for Δz = z1 - z2. (a) Δz = 0.2 mm, (b) Δz = 0.3 mm, and (c) Δz = 0.4 mm, respectively. The overall length of the device is z1 = 1.0 mm and results in approximately 3-db attenuation of the input signal. This figure indicates that the output behavior of the unequal-arm-length NLMZ is sensitive to Δz and, for the given power range and device length, nonlinear phase shifts in excess of π are attainable. The 1-mm-length device would be hard to fabricate for Δz's as large as 0.4 mm, but the difference in length must be greater than 0.2 mm to observe nonlinear behavior with reasonable power levels. Larger Δz's are possible for larger device lengths, but the absorption would be excessive. Also, the design of the device introduces a linear phase difference between the arms which changes the output characteristics for each given Δz. The difficulties encountered with the unequal-arm-length NLMZ are alleviated by employing an equal-arm-length NLMZ. For this geometry, the nonlinear behavior arises from the control input and the linear phase difference is eliminated. The signal input remains constant while the control input is varied and, therefore, the modulation is around some constant value. The fabrication of this device, however, requires a more stringent design, since it must support two orthogonal fundamental modes and have multiple inputs and use an output polarizer. Figure 3 illustrates the signal output of the rib-waveguide equal-arm-length NLMZ as a function of input-control power for two signal inputs. For simplicity, the control input is limited to one arm of the device. The device length is 0.8 mm and results in approximately 3-db attenuation of the signal. For low signal levels (0.1 mW in each waveguide) one obtains a net nonlinear phase change of approximately 7π across the length of the device. Note that the rate of oscillations of the output signal is decreasing with increasing control levels because of the saturation of the nonlinearity (since the device requires larger changes in the control power for any additional increase in the nonlinear index change). Likewise, if the signal-power level is increased, the available nonlinear-index change is decreased because of saturation effects in bulk GaAs and the resulting nonlinear phase change is decreased. This is clearly demonstrated for the signal input of 0.5 mW into each arm, where the net nonlinear phase change is 4π for the higher control powers.
CONCLUSION

A perturbation theory was used to model the equal- and unequal-arm-length NLMZ's fabricated in bulk GaAs. The plasma theory was used to calculate the carrier density-dependent index of refraction and absorption. Carrier diffusion effects were also included in the model. Large nonlinear phase shifts were observed in both devices, which theoretically implies the devices should work in bulk GaAs. The equal-arm-length NLMZ performed much better than the unequal-arm-length NLMZ since the nonlinear phase difference accumulates over the whole device, while the cost for the better performance was an increased complexity in device design and fabrication.

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