Eyes on the Sky: All-Optical Sensor Based on Nonlinear Modal Interferences

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Abstract. In this study, we propose an all-optical sensor based on consideration nonlinear effects on modal propagation and output intensity. The sensor can be tuned to highest sensitivity in the refractive index ranges sufficient to detect protein-based molecules, other water-soluble chemical, and air-pollutions. The nonlinear regimes show the capability to operate on any choice of materials for ridge waveguide. Crystalline polydiacetylene has high third-order susceptibility, thus could be best candidate for core material. This material in presence of nonlinear effect is studied in the multimode waveguide with NMPA method that promises to investigate the coupler in small lengths. The visible changes of field intensity at output facet in various surrounding layer refractive index show the high sensitivity to the refractive index of surrounding layer that is foundation of introducing a sensor. Also, the results show the high distinguished changes on modal propagation in various refractive index of surrounding layer. To the best of our knowledge this is the first time that a nonlinear MMI in a few micrometers is proposed as a robustness sensor. In fact, this paper brings a useful and powerful way to progress the all optical sensors based on MMI couplers.

Keywords: MMI, NMPA, all-optical sensor, mode, waveguides.

INTRODUCTION

Multimode interference couplers [1] have recently become key elements of planar integrated photonics. These couplers have significant features such as low loss and crosstalk [2], high optical bandwidth [3], compact size [4], low sensitivity to input polarization [5], low sensitivity to operating wavelength [6], and tolerance to fabrication errors. MMI couplers have broad applications in photonic complex circuits, one of the important application is all-optical sensor especially when operated in the nonlinear regime. MMI coupler have been widely used for the variety of sensing proposes among them temperature, pressure and chemical/biological sensors in which the change in refractive index is read out as change in output intensity [7-9]. Some MMI sensors have been introduced with changes in the configuration of MMI coupler to have smaller length of self-imaging formation whereas they are modeled in long length and complicated structures [9].

The nonlinear MMI coupler as active device is more sensitive to input characterization and region environment that can be effective subjects to change the interference mechanism among the guided modes. Absolutely, nonlinear regimes might be more sensitive to the refractive index of surrounding and core layers due to the direct influence on refractive index. Therefore, nonlinear MMI coupler has the ability to show an accurate sensor.

In this paper, nonlinear modal propagation analysis (NMPA) [10-16] method is studied in multimode interference waveguide as a novel and high potential approach for detecting the air-pollution, water-soluble materials, and any change in surrounding environment. Each change in surrounding layer lead to a change in refractive index or wavelength might predict different mode effective indices also interference mechanism that demonstrate the visible differences in output field profile. The high changes of output intensity that is created in effect of variety of surrounding layers prove the high performance of proposed sensor. Notably, this nonlinear device, could demonstrate reaction to others such as light, acoustic wave, and temperature, moreover, the changing in surrounding layer.

NONLINEAR MODAL PROPAGATION ANALYSIS

The MMI coupler is introduced to the photonic devices as the simplest structure. Although this device has broad applications in the integrated photonic circuits and telecommunications, these applications increase with the
appearance of nonlinear effects due to the change in the modes of electric field in terms of amplitudes or phases. This application exchanges energy among modes [15]. This advantage leads to an ability to control the wave propagation in the medium contributing to signal processing in all-optical functions [13].

The central region of MMI coupler is the multimode waveguide. The access waveguides which are usually single mode are fixed at the input and output facets of the multimode waveguide. The performance of these devices depends on the interference of guided modes, where the complete constructive interference contributes to the formation of the single or multiple self-images at precise distances in the input facet. The interference property of the MMI waveguide intensely depends on the refractive indices of the core and cladding regions of the Multimode waveguide. In other words, by varying the refractive index in the core region, modal interferences phenomena are also changed. In fact, by imposing the intense light into the multimode region, core refractive index becomes a function of intensity in the presence of Kerr nonlinear effect; as the result, the modes propagate in a different situation according to changes of optical properties. By studying this effect in the Multimode interference couplers and applying the obtained results, we can design an all-optical sensor to have small MMIs. In this section, we theoretically study the nonlinear effects in an MMI coupler by studying the Nonlinear Modal Propagation Analysis (NMPA) method in the central region.

The refractive index is shown in Fig. 2 indicates our design. In fact, MMI coupler is assumed as a conventional structure. Notably, $n_{\text{MMI}}$ must higher than $n_{\text{cladding}}$ to confine the light in core region that originate from total reflection basis. Critical angle determines the mode expansion in lateral direction depends on core and cladding layer refractive index and corporation the boundary condition, guided modes are discreet, which as shown in theory of optical waveguides. In other word, critical angle indicates the guided modes number.

The MMI region is isotropic, and the field in this region is a superposition of all the modal fields of the MMI. The details of MPA method exist anywhere [1,17]. For studying the NMPA, the amplitude of the modes are considered as a function of propagation direction not only shows phase and amplitude changes in region but also the exchange of energy among modes (in the z direction) whereas in linear regime, the amplitude of the modal fields is constant in the nonlinear regime. Therefore, we follow the conventional MPA while considering the mode

![FIGURE 1. Schematic structure of MMI coupler](image1.png)

![FIGURE 2. Refractive index in a ridge waveguide](image2.png)
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amplitudes as a function of propagation direction, and then solve the nonlinear coupled equations of guided modes to obtain the electric field throughout the MMI region for applying the Kerr effect on MPA and proposing NMPA.

When an intense input light launches into the MMI region from the input waveguide, the refractive index of the region changes by an amount that is proportional to the intensity of the input light. In fact, varying the intensity of the input light produces a nonlinear change in the refractive index of the MMI region. The change of the refractive index leads to a change in the interference of the modes and in the fold-imaging formation.

The height of MMI coupler is considered to be 1μm that lead to just excite a mode in vertical direction (y) so that there is a propagation constant in this direction. The light distribution in 3D is expressed as

$$
\psi(x, z, t) = \sum_{\nu=0}^{a} \Phi_{\nu}(z)e^{i \beta_{\nu} z}e^{i k_{x} x}e^{i k_{y} y}e^{-(\omega t + \phi_{\nu})}
$$

After substitute above equation in nonlinear wave equation the below equation is obtained

$$
\sum_{\nu} \left[ \frac{d^{2} \Phi_{\nu}(z)}{dz^2} + 2 j \beta_{\nu} \frac{d \Phi_{\nu}(z)}{dz} - (\beta_{\nu}^{2} + \gamma_{\nu}^{2} + k_{y}^{2}) \Phi_{\nu}(z) 
+ n^{2} \Omega^{2} \Phi_{\nu}(z) \right] e^{i k_{x} x} e^{i k_{y} y} e^{-j \omega t}
\quad = -\frac{3 \chi_{3}^{(3)} \Omega^{2}}{c^{2}} \sum_{\rho} \sum_{q} \sum_{s} \left[ \left( \Phi_{\rho} \Phi_{q} \Phi_{s}^{*} \right) e^{i (\gamma_{\rho} + \gamma_{q} - \gamma_{s}) x} e^{i (\beta_{\rho} + \beta_{q} - \beta_{s}) z} e^{-j \omega t} 
+ \left( \Phi_{\rho} \Phi_{q} \Phi_{s}^{*} \right) e^{i (\gamma_{\rho} + \gamma_{q} - \gamma_{s}) x} e^{i (\beta_{\rho} + \beta_{q} + \beta_{s}) z} e^{-j 3 \omega t} \right]
\right]
\quad \psi_{y}(x, z, t)
$$

The second term indicate third-harmonic generation here. The explained procedure in our study can be used for third-harmonic generation too with considering the mentioned term in solving the nonlinear coupled equations and obtain the modes electric field in the launched and generated frequency; however, because of switching application on \( \Omega \) frequency (same frequency as the input) we avoid to consider the third harmonic generation and omit the related term. From the above equation we have a dispersion equation as

$$
\beta_{\nu}^{2} + \gamma_{\nu}^{2} + k_{y}^{2} = n^{2} k_{0}^{2}
$$

$$
\beta_{\nu}^{2} + \gamma_{\nu}^{2} = n^{2} k_{0}^{2} - k_{y}^{2}
$$

$$
= (n^{2} - (k_{y}^{2}/k_{0}^{2})) k_{0}^{2}
$$

In compare the above equation with Eq. (6) the effective refractive index for core layer is obtained as

$$
n_{MNI} = [(n^{2} - (k_{y}^{2}/k_{0}^{2}))^{0.5}
$$

The core refractive index affects from surrounding layer refractive index as shown in Eq. 5. Notably, the penetration depth of each mode into the cladding region is very small, and has the negligible effect on the device performance, then the clad refractive index does not has contribution to this effective refractive index in this study, the negligible penetration and single mode in the vertical direction make procedure of EIM easy. In the above method EIM is not an approximation against the other. Notably the vertical profile of electric field does not change from input waveguide to the MMI then access waveguides should follow the MMI and consider in 2D because they have 100% overlap in the y direction due to the having same mode in y direction.

In fact, the electric field in y direction is not affected from the nonlinear medium and no need to indicate it in the electric field that is the deal of study the medium in 2D. Therefore field distribution of the light in MMI region is expressed by:
\[ E(x,z,t) = \sum_{\nu=0}^{n} A_{\nu}(z)e^{i\gamma_{\nu}x}e^{i\beta_{\nu}z}e^{-i\omega t+\phi_{\nu}} \]  

(6)

where \( \nu \) is the mode number, \( A_{\nu}(z) \) is the amplitude of the \( \nu \)-th mode that contains real and imaginary parts, \( \gamma_{\nu} \) and \( \beta_{\nu} \) are lateral and longitudinal propagation constants of the \( \nu \)-th mode, respectively. With the appearance of the nonlinear effect in the MMI region, the refractive index of this region changes and takes a nonlinear part. The total refractive index of the MMI region is then given by:

\[ n = n_{\text{MMI}} + n_{2}I = n_{\text{MMI}} + n_{\text{NL}} \]  

(7)

where \( n_{\text{MMI}} \) is the usual weak-field refractive index of guiding structure (linear term), \( I \) denotes the intensity of the input light, and \( n_{\text{NL}} \) is the nonlinear refractive of the Kerr nonlinear effect.

Here, the most important purpose is applying the NMPA to study the nonlinear phenomenon which are induced in the multimode waveguide that launched with linearly polarized wave, such phenomenon could induce some desirable effects on mode propagations and interactions as in the next will be discussed.

The nonlinear modes equation for MMI coupler which is fulfilled NMPA is (from equation 2 [13])

\[ 2j\beta_{\nu} \frac{d\phi_{\nu}(z)}{dz} = -\frac{3\chi^{(3)}}{c^{2}}\omega^{2}\sum_{p}C_{\nu}(p,q,s)(\phi_{p}\phi_{q}\phi_{s}^{*}) \]  

(8)

where \( C_{\nu}(p,q) \) are the overlap coefficients of the different modes. Here, it is important to highlight that the right-hand side of Eq. (10) includes self-phase modulation terms \( (p=q=v=s) \), cross-phase modulation terms \( (p=v\neq q=s) \), and terms that lead to power exchange among the modes. This equation has been verified experimentally by Magana-Cervantes et al. [14]. This set of coupled numerical differential equations can be solved using a high-accuracy FDM, but this is time consuming, and memory limitations restrict its application to small low-intensity nonlinear MMI.

By solving the set of coupled equations of the field amplitudes \( \nu = 0,\pm1,\pm2,\pm3,... \), the field amplitude \( A_{\nu}(z) \) of the modes is obtained. Consequently, by using Eq. (1), the field in MMI region will be obtained; numerical solve shows the amplitudes as Interpolating Function that are complex numbers. For clarify, we bring some result of self-phase and cross-phase modulation and wave-mixing.

**FIGURE 3.** Normalized field electric field in MMI length.
In self-phase modulation effect, the sinusoidal profile is converted to the Gaussian profile without change in the amplitude maximum. Fig. 4 show self-phase modulation. However, changes in wavelength, amplitude maximum and wavelength shift between two modes originate from cross-phase modulation, wave-mixing, respectively. The field profile of the guided modes, in general, consists of a superposition of sine and cosine light waves, with zero fields at the boundaries of the guiding region.

In addition, we assume that there is negligible penetration of the fields in the cladding layer as well as Goos-Hanchen shift due to the high contrast index which is increased by imposing the nonlinearity. The field amplitude in output port is obtained by evaluating the summation of overlap integral between the profile of an output waveguide and the profile of the excited modes of the MMI region.

\[
E_{0r,m,n} = \frac{\int A_r (L) e^{\gamma x} \cos[k_x (x - (-1)^{m+1} d) + \phi_0] dx}{\left[ \int e^{\gamma x} \cos[k_x (x - (-1)^{m+1} d) + \phi_0] dx \right]^2}^{1/2}
\]  

(9)

By calculating the summation of above equation regards to the outputs, the electric field in slightly output is obtained.

**MODELING RESULTS AND DISCUSSION**

The MMI switch operates in a situation where the variation of the switching state is required in the input intensity variation and, at least, two input intensities for switching performance are considered. In this section, the procedure for accessing the optimum switch of the SPG and insertion loss are studied as the function of MMI length, input electric field and output waveguides width in switching states variation. Our considerations are limited to the MMI coupler with the following structure, \( n_c = 1, n_{MMI} = 1.56, W_{MMI} = 10 \mu m, d = 4.5 \mu m, b = 1.5 \mu m, \chi^{(3)} = 8.4 \times 10^{-18} \text{m}^2/\text{W} \) at \( \lambda_0 = 1.55 \mu m \), these parameters show: refractive index of clad (Air) and core (Glass), effective width, transversal distance between of multimode waveguide center and single input waveguide centers, input waveguides width, third order susceptibility and input wavelength, respectively.

In modeling results, the output intensity changes in variety of cladding refractive index for two category, air pollution in three different wavelength and liquid-solvent, in air range of refractive index, three wavelength are implemented to prove the capability of device to detect chemical, biological acoustic sensor. The field distribution in 25 \( \mu m \) of multimode region is studied in several clad layers to show the sensitivity of modal interference to cladding refractive index in nonlinear regime, it shows a broad application which as are due to change in the medium. Figure 2 shows output intensity as a function of input intensity. This result show the high oscillation around 1000 W/\( \mu m^2 \), thus we choose this input as a sensor input intensity.

**FIGURE 4.** Output intensity as a function of input intensity where refractive contrast index is 0.56 and wavelength is 1550 nm
Fig. 3 demonstrates output intensity in range of air refractive index in 1550, 1530 and 1300 nm wavelength. Due to the more oscillation in 1530nm, it can be good candidature for air sensing.

FIGURE 5. Output intensity as a function of cladding refractive index in air range where wavelength is a. 1550, b. 1530, c. 1300.

Water-soluble refractive index range is the best candidate to sensing biologically. Therefore, we apply our design in 1530nm of wavelength in range of 1.3-1.5 cladding refractive index. The result demonstrates in Fig. 3 and it is shown that there is high oscillation in output intensity in the mentioned range.

FIGURE 6. Output intensity as a function of cladding refractive index in range 1.3-1.5 where wavelength is 1540.

Mode interferences is basis of multimode interferences that will become stronger in a nonlinear regime due to cross-phase modulation and wave-mixing effects. Here we are going to show the contribution of cladding refractive index on interference. Therefore, we indicate the field distribution in some cladding layer in ranges of air and water.

FIGURE 7. Field distribution where cladding refractive index is a. 1, b. 1.1, c. 1.33, d. 1.44, and e. 1.5.
CONCLUSIONS

We propose an all-optical sensor based on NMPA in MMI coupler. The sensor can be tuned to highest sensitivity in the refractive index ranges sufficient to detect water-soluble chemical or biological materials and air-pollution. The Kerr nonlinear effect is studied to access the high efficiency sensor to operate on any choice of materials for slab waveguide even conventional glass, also possibility to design The result show visible changes on field distribution in MMI region on various surrounding layer refractive index that show high sensitivity to the refractive index of surrounding layer. The sensitivity to wavelength determines the possibility of design all-optical earthquake sensor due to the reaction of nonlinear mechanism to any change in the system environment.

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