# Optical waveguide electric field sensor with controllable operating point using asymmetric Mach-Zehnder structure*

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For an integrated electro-optical sensor, the operating point has a significant effect on the performance of the sensor. In this paper, an optical waveguide electric field sensor with controllable operating point is designed using $LiNbO_3$ materials, which has an asymmetric Mach-Zehnder interferometer (MZI) structure. Theoretical results show that the optimal operating point can be obtained and controlled by tuning the output wavelength of the tunable laser used in the sensing system. The simulation results show that the sensitivity about 83 dB·μV/m can be obtained, and the linear dynamic range as large as 60 dB can be achieved. And the fabrication tolerance of the center-to-center distance for the 3 dB coupler used in the asymmetric MZI is ~0.5 μm, while the power splitting ratio of the Y branch is with more tolerance.

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Operating point is a key factor in the behavior of integrated electro-optical sensor, which determines the sensitivity and linear dynamic range in the sensing system[1,2]. For conventional electric field sensor based on MZI, the waveguide length must be adjusted with a precision on the submicron order. However, it is difficult to achieve such a precision in the waveguide fabrication process because of titanium diffusion[3,4] and proton exchange[5,6]. Recent reports showed that the operating point of sensors fabricated by appealing proton-exchange can deviate from the ideal operating point as large as 14.5°[7]. In addition, operating point can shift with the changes of environmental conditions, including temperature, humidity and stress[8,9].

To solve the optical bias problem, some approaches have been proposed. First, changing the polarization state can adjust and make the operating point of the electro-optical sensor stable. As mentioned in Ref.[10], it can make the root mean square (RMS) signal fluctuations lower than 0.2 dB, when the temperature is 30°C. However, it can only be applied to the sensor fabricated from bulk crystals and discrete coupling lenses. Second, applying a bias voltage, which is supplied by power from a separate uplink laser to a small photovoltaic array at the sensor head[11], to electrodes on the waveguide can adjust the operating point of sensors efficiently. But the application of voltage source can make the operating point unstable, and disturb the field under measurement at the same time. Finally, changing the output wavelength of the laser used in the system is undoubtedly the best way to control the operating point, because it's simple, passive, without auxiliary devices and easy for operation. It is mentioned in Ref.[12]. However, no further experimental research was reported yet.

In this paper, an optical waveguide electric field sensor with an asymmetric MZI structure and using a tunable laser as light signal source is designed. An appropriate length difference between the two arms of MZI structure can be obtained, and thus the operating point is adjusted into an ideal linear region by tuning the input wavelength. As a result, the sensitivity can be improved, and the linear dynamic range can be broadened significantly. At the same time, the fabrication tolerance of the center-to-center distance for the 3 dB coupler and the power splitting ratio for the Y branch can be accepted.

The sensor discussed in this paper is based on an asymmetric MZI structure with the output Y-branch substituted by a 2×2 directional coupler whose length difference between two arms comes from parallel linear and cosine bend waveguides as shown in Fig.1. The single-mode light signal is divided into two parts by the input Y-branch, and it can be described as follows[13]:

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$$E_3 = a\exp[\mathrm{j}(\Delta\varphi + \varphi_0)/2], \tag{1}$$

$$E_4 = b\exp-[\mathrm{j}(\Delta\varphi + \varphi_0)/2], \tag{2}$$

where $a^2+b^2=P_{in}$, in which $P_{in}$ is the input power, and $a$ and $b$ are electric field amplitudes at ports 1 and 2, respectively; $\varphi_0=\beta_0\Delta L+\varepsilon$, in which $\varphi_0$ is the initial phase of the incident light, $\beta_0$ is the transmission constant of the waveguides, $\Delta L$ is the length difference between two waveguide arms, and $\varepsilon$ is the phase deviation resulting from fabrication process and the operating point shift; $\Delta\varphi$ is the phase caused by potential difference between electrodes on waveguides, and $\Delta\varphi=\pi V_g(t)/V_\pi$, in which $V_\pi$ is the half-wave voltage, and $V_g(t)$ is the received signal on electrodes.

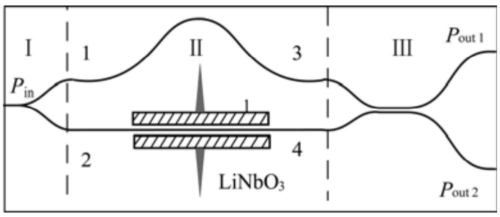



**Fig.1 Structure diagram of the proposed electric field sensor including Ⅰ Y-branch at input, Ⅱ two arms of the asymmetric MZI structure and Ⅲ 3 dB coupler at output**

Ignoring the transmission loss, the transfer matrix of the directional coupler can be written as[7]:

$$\begin{pmatrix} E_{o1} \\ E_{o2} \end{pmatrix} = \mathrm{e}^{-\beta L_c} \begin{pmatrix} \cos kL_c & -\mathrm{j}\sin kL_c \\ -\mathrm{j}\sin kL_c & \cos kL_c \end{pmatrix} \begin{pmatrix} E_3 \\ E_4 \end{pmatrix}, \tag{3}$$

where $L_c$ is the interaction length, and $k$ is the coupling coefficient. According to Eqs.(1)−(3), the power of the output light is

$$P_{out1} = a^2\cos^2(kL_c) + b^2\sin^2(kL_c) - ab\sin(\Delta\varphi+\varphi_0)\sin(2kL_c), \tag{4}$$

$$P_{out2} = 1 - P_{out1}. \tag{5}$$

When the Y branch is exactly symmetric, and the 2×2 directional coupler is an ideal 3 dB coupler, we can get $a^2=b^2$, and $kL_c=(2m+1)\pi/4$, ($m$=0, 1, 2…). Supposing $P_{in}=1$, Eqs.(4) and (5) can be simplified as

$$P_{out1} = 1/2[1-\sin(\Delta\varphi+\varphi_0)], \tag{6}$$

$$P_{out2} = 1/2[1+\sin(\Delta\varphi+\varphi_0)]. \tag{7}$$

When $\varphi_0=\beta_0\Delta L+\varepsilon= n\pi$ ($n$=0, 1, 2…), and $\Delta\varphi<<1$, Eqs.(6) and (7) can be further simplified as

$$P_{out1} = 1/2\left[1+(-1)^n\Delta\varphi\right], \tag{8}$$

$$P_{out2} = 1/2\left[1-(-1)^n\Delta\varphi\right]. \tag{9}$$

Based on Eqs.(8) and (9), the output power of the device is proportional to the input voltage signal on electrodes. Moreover, the voltage signal can reach the maximum amplitude, and it means that $\varphi_0=n\pi$ is the ideal operating point. At the same time, the power of the two output ports can be equal if there is no voltage signal between electrodes. Therefore, the operating point can be retained as $n\pi$ by tuning the output wavelength of the laser, because $\beta_0$ is related to the wavelength.

It is worth mentioning that the sensor structure is a symmetric M-Z interferometer when $n$=0. Assuming the directional coupler is an ideal 3 dB coupler and the Y branch is exactly symmetric, the operating point is in an excellent linear region which is immune to the wavelength variation. However, the Y branch can not be exactly symmetric, and the coupler is no longer an ideal 3 dB coupler in actual situation. As a result, the power of the two output ports can not be equal even in a wide wavelength range, and the operating point is not in linear region any more, as shown in Fig.2.

To avoid this situation, an asymmetric M-Z structure ($n\neq0$) is used to make sure the operating point in an ideal position as mentioned above. On the other hand, the transfer function of the sensor is symmetric sinusoidal periodic function in accordance with Eqs.(6) and (7). In order to ensure arbitrary angle that the operating point deviates can be adjusted successfully, the output power should cover half of the period at least. Assume that the wavelength varies in C band, the operating wavelength is 1550 nm, and $n$=40. According to $\varphi_0=\beta_0\Delta L+\varepsilon= n\pi$, when $\varepsilon\approx0$, we can get $\Delta L$= 14.5 μm. Then the output power of the electric field sensor in C band can be obtained, as shown in Fig.2. As we can see, the horizontal coordinate of the interaction point is the optimal operating wavelength, which means that the operating point is in the ideal position at this wavelength.

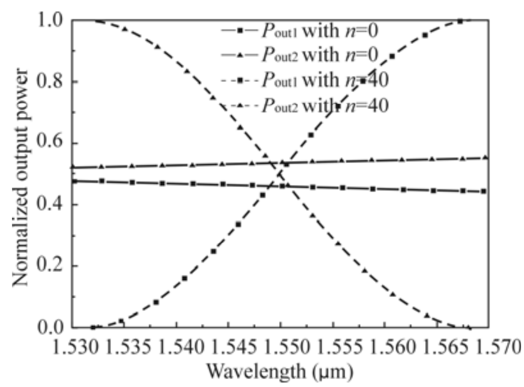



**Fig.2 Output power of the electric field sensor in C band with different $n$ ($\varphi_0=\beta_0\Delta L+\varepsilon=n\pi$) and output power**

However, due to the fabrication tolerance and the changes of environmental conditions, $\varepsilon$ can not be ignored. The intersection point of the output power shifts horizontally as shown in Fig.2. But no matter how much the intersection point shifts, there is an intersection point of the output power in half of the period. Therefore, the ideal operating wavelength can be found by tuning the output wavelength in C band, as long as the power values of the two output ports become equal.

The measurement accuracy of a sensing system depends partially on the properties of the integrated electro-optical sensors. Our discussion focuses on those characteristics of the sensor, such as sensitivity and linear dynamic range in this paper.

Sensitivity is defined as the minimum electric field intensity which can be measured in an electric field sensing system. Usually, the electric field intensity is regarded as the sensitivity in the sensing system when the power values of signal and noise become equal[14]. Considering thermal noise, dark current noise, shot noise and relative intensity noise, we can get

$$E_{\min}=\frac{C_{\mathrm{d}}+C_{\mathrm{m}}}{C_{\mathrm{d}}h_{\mathrm{e}}}\frac{V_{\pi}\sqrt{2B}}{\pi R\alpha\left[ab\sin(2kL_{\mathrm{c}})\right]\cos\varphi_0}\times \sqrt{i_{\mathrm{p}}^2 RIN+2e(i_{\mathrm{p}}+I_{\mathrm{D}})+\frac{4KT}{R_{\mathrm{L}}}}, \tag{10}$$

where $K$ is the Boltzmann constant, $T$ is the absolute temperature, $B$ is the detection bandwidth, $e$ is the charge of an electron, $R_{\mathrm{L}}$ is the resistance terminating the photodiode, $I_{\mathrm{D}}$ is the dark current of the photodiode, $i_{\mathrm{p}}$ is the average current of the photodiode, $RIN$ is the relative intensity noise, $R$ is the responsivity of the photodiode, $\alpha$ is the loss coefficient, $C_{\mathrm{d}}$ is the capacitance of the antenna, $C_{\mathrm{m}}$ is the effective capacitance of the electrodes, and $h_{\mathrm{e}}$ is the effective height of the antenna.

The linear dynamic range can be described as the ratio of the maximum and the minimum allowable signal power. The maximum signal can be determined by the third harmonic magnitude when $\varphi_0\approx n\pi$. Otherwise, the minimum signal is generally set by the second harmonic[15]. The minimum signal can be defined as the point where the modulating voltage produces a fundamental signal equal to the aforementioned noise. Expanding Eqs.(6) and (7) as Bessel series[16], we can get that the fundamental modulation is $\frac{M\pi V_{\mathrm{g}}\cos\varphi_0}{V_{\pi}\left(N-M\sin\varphi_0\right)}$, the second harmonic modulation is $\frac{M\left(\pi V_{\mathrm{g}}\right)^2\sin\varphi_0}{4V_{\pi}^2\left(N-M\sin\varphi_0\right)}$, the third harmonic modulation is $\frac{M\left(\pi V_{\mathrm{g}}\right)^3\cos\varphi_0}{24V_{\pi}^3\left(N-M\sin\varphi_0\right)}$, where $M=ab\sin(2kL_{\mathrm{c}})$, $N=a^2\cos^2(kL_{\mathrm{c}})+b^2\sin^2(kL_{\mathrm{c}})$.

We can assume that $h_{\mathrm{e}}$=2.56 mm, $C_{\mathrm{d}}$=0.9 pF, $C_{\mathrm{m}}$=2 pF, $B$=1 kHz, $R$=0.6 A/W, $P_{\mathrm{in}}$=1 mW, $\alpha$= -7 dB, $RIN$= -165 dB, $I_{\mathrm{D}}$= 5 nA, $T$= 300 K, $R_{\mathrm{L}}$= 1 kΩ, $\beta_0\Delta L=n\pi$ at 1550 nm, and the transfer function of the sensor is symmetric sinusoidal periodic function as mentioned above. According to $\varphi_0=\beta_0\Delta L+\varepsilon$, we can use the variation of $\varepsilon$ from 0 to $\pi/2$ as the operating point's influence on sensitivity and linear dynamic range in the sensing system as shown in Fig.3. As we can see, the sensitivity about 83 dB·μV/m (order of μV/m) can be obtained, and the linear dynamic range as large as 60 dB (from μV/m order to V/m order) can be achieved when the operating point is in an ideal position ($\varphi_0=n\pi$ and $\varepsilon$=0). As the operating point deviates from the optimal operating point, the sensitivity tends to get larger, and the linear dynamic range becomes narrower in the meantime. When $\varepsilon\approx\pi/2$, the sensitivity can increase to 120 dB·μV/m, and the linear dynamic range also reduces to 10 dB. Hence, it can be concluded that the operating point has a significant effect on the sensitivity and linear dynamic range. The operating point can be retained near $n\pi$ by tuning the input wavelength as mentioned above. As a result, the sensitivity and linear dynamic range can be improved remarkably.

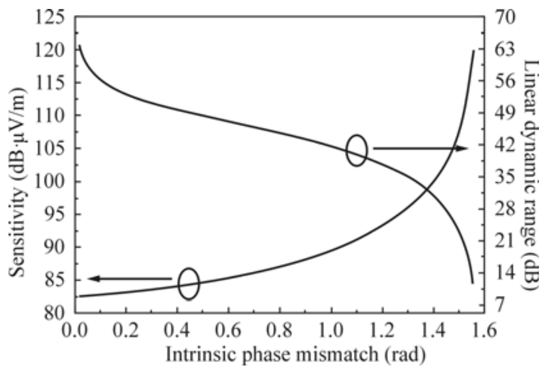
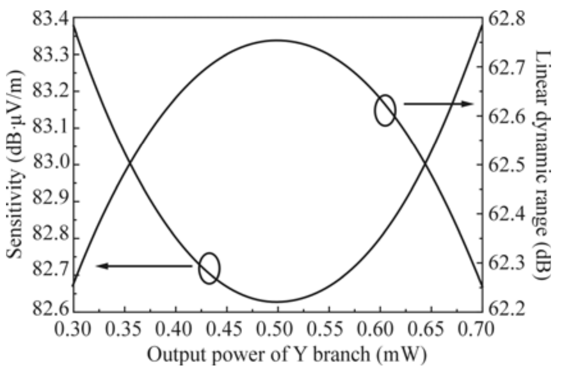



**Fig.3 Sensitivity and linear dynamic range when operating points are different**

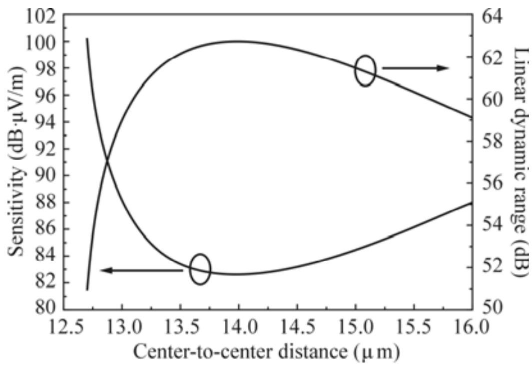
Due to the fabrication process, the Y branch can not be exactly symmetric, and it means that the power splitting ratio of the Y branch can't be 1. Besides, the main parameters of 3 dB coupler, such as the interaction length and the center-to-center distance, would also be different with the values designed. We know that the interaction length is several millimeters, and the center-to-center distance of the waveguide is several micrometers. Therefore, ignoring the error of the interaction length, our discussion focuses on the influence caused by the power splitting ratio of the Y branch and the center-to-center distance for 3 dB coupler, as shown in Fig.4.

It can be seen that the changes of the sensitivity and linear dynamic range are less than 1 dB·μV/m and 1 dB, respectively, when one of the output power of the Y branch varies in the range between 0.3 mW and 0.7 mW, as shown in Fig.4(a). Thus, a conclusion can be drawn that the performance of the sensor is not sensitive to the power splitting ratio of the Y branch. While for the center-to-center distance of 3 dB coupler, the sensitivity gets larger when it deviates from the designed value 14 μm, as shown in Fig.4(b). Especially, when it's in the range of 12.7−13.5 μm, the sensitivity rises by 20 dB·μV/m. Similarly, the linear dynamic range becomes narrower when the center-to-center distance deviates from 14 μm, and the change gets stronger if it is less than 14 μm.

Consequently, we can conclude that the error of the center-to-center distance can't be neglected. But the influence on the performance of the sensor can be cut down obviously when the error of the center-to-center distance is lower than 0.5 μm.




(a) Sensitivity and linear dynamic range when output power values of Y branch are different




(b) Sensitivity and linear dynamic range when center-to-center distances of 3 dB coupler are different

**Fig.4 Influence of different structure parameters on device performance**

An optical waveguide electric field sensor with an asymmetric MZI structure is designed. Theory and simulation analyses show that changing the operating wavelength can make the operating point at the optimal position, and an optimal operating point can improve the sensitivity and linear dynamic range in the sensing system effectively. And the fabrication tolerance of the center-to-center distance for the 3 dB coupler is ~0.5 μm, while the power splitting ratio of the Y branch is with more tolerance.

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