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High sensitivity bulk electro-optic modulator field sensor for high voltage environments

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An optical electric field sensor is an effective instrument for surveying the electric or magnetic field around a high voltage electrical system. A Mach-Zender interferometer type modulator is generally used in this kind of sensor. The sensor has good sensitivity to electric or magnetic fields, but an unexpected high field could easily destroy the modulator owing to its short electrode separation. A bulk modulator usually has long separation between the two electrodes, which can prevent modulator breakdown, but its sensitivity is usually worse than the Mach-Zender interferometer type sensor. To solve this problem, a Fabry-Perot cavity is used to improve the sensitivity of the bulk modulator type sensor. This work also discusses the optimization of the sensor sensitivity. When the sensor works on the point where a cavity resonance has maximal slope, the proposed sensor has approximately the same sensitivity for sensing a field as the Mach-Zender interferometer type sensor. © 2004 American Institute of Physics. [DOI: 10.1063/1.1818492]

In research on high voltage electrical systems, measurement equipment is easily attacked by unexpected electrical shocks through the metal cable of the sensor. Sensing by optical sensors and transmitting the signal by a laser light or an optical fiber can improve the situation. Therefore numerous optical high voltage sensors have been developed.¹⁻⁷ Besides the high voltage sensing, a need also arises to survey the electrical field near the high voltage system. An optical electric field sensor⁸⁻¹⁰ appears to be a promising candidate for such an application.

The sensor is typically based on an electro-optic modulator (EOM). Laser light transmits to the modulator and back to an optical detector via fibers. The structure of the sensor resembles that of an optical voltage sensor, except that the electrodes of the EOM are attached to a dipole or loop antenna to detect the electric or magnetic fields. The antenna creates a potential difference between the two electrodes of the EOM. This potential difference modulates the light that passes through the modulator. The amplitude of the modulated light is roughly proportional to the strength of the electric or magnetic field. Moreover, the modulated light is transformed into an electronic signal via an optical detector and an amplifier.

The EOM of an optical electric field sensor is usually a Mach-Zender interferometer modulator. The electrodes of the modulator are generally separated by only a few tens of microns for high sensitivity. Generally, the V_{π} , the half wave voltage for this kind of modulator, is approximately 5–10 V. The small V_{π} gives good sensor sensitivity, but the small

separation of the electrodes sometimes causes modulator breakdown if an unexpectedly high voltage is added on to the antenna or electrodes. To solve the problem, a bulk electro-optic phase modulator with large electrode separation is used in this work to replace the Mach-Zender interferometer EOM. The change strengthens the resistance of the sensor to electric attack, but also increases its V_{π} to approximately 200 V. The V_{π} increase clearly downgrades the sensitivity of the sensor. Therefore this study employs a Fabry-Perot cavity to improve the sensor sensitivity. A Fabry-Perot cavity is located around a phase modulator, and one side of the resonance peak of the cavity is used as the electric field discriminator. The laser wavelength is locked to the side of a resonance of the cavity using a low bandwidth feedback loop, and the modulation of the phase modulator changes the optical path of the cavity, thus changing the intensity of the light output from the cavity. The cavity can be used to build a sensor suitable for measuring the field near a high voltage system with similar sensitivity to a Mach-Zender interferometer sensor but better electrical shock resistance. This study also discusses how the optimal sensitivity can be obtained from a specified cavity.

Figure 1 depicts the experimental setup. The experiment is conducted using a 40-mm-long commercial MgO:LiNbO₃ phase modulator. The electrodes are deposited on the two wide surfaces of the modulator with a 2 mm separation. Moreover, the electrodes are connected to a SMA connector with bond wires. The signal from the antenna for detecting the electric field or the testing signal from a function generator can feed to the electrodes via the connector. This study uses a function generator to test the sensor performance. The optical input and output surfaces of the modulator are coated with AR coating at visible laser wavelength. Moreover, the

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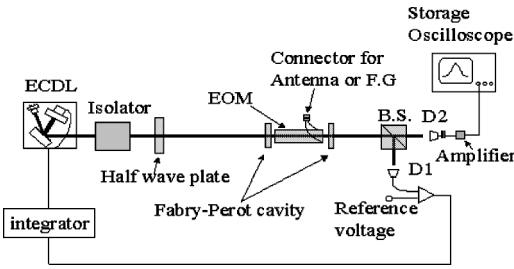


FIG. 1. The experimental setup for the electric field sensor constructed by a bulk phase modulator and a Fabry-Perot cavity.

cavity mirrors are two plane mirrors with reflectivity of 87%, and have separation of 100 mm. Furthermore, the laser source is an extended cavity diode laser (ECDL) with its center wavelength at 657 nm. The wavelength of the laser source can be tuned by a PZT for more than 120 GHz without mode hopping. The laser beam passes through a half-wave plate to select a suitable polarization for the modulator, and then passes the cavity. After the cavity the beam passes a beam splitter, which divides it into two. One of these two beams hits the detector D1. The signal from D1 is subtracted from a reference voltage and serves as the feedback signal, which is used to lock the laser wavelength to a selected level on one side of the cavity resonance. The bandwidth of the servo electronics is below 1 Hz to prevent the canceling of the modulating signal. The other beam goes to a detector D2. The signal is amplified and observed via an oscilloscope or spectrum analyzer.

The sensitivity of using the resonance of a Fabry-Perot cavity depends on where the laser wavelength is locked. Airy's formula¹¹ can be used to estimate the point with the sharpest slope. The sensitivity is optimized if the laser wavelength is locked to this point. The transmitted intensity $T(\theta)$ of a Fabry-Perot cavity can be expressed using the following Airy's formula:

$$T(\theta) = \frac{I_t}{I_i} = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2(\delta/2)} = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2(\theta)}, \quad (1)$$

where I_i and I_t denote the intensity of the incident wave and the transmitted wave, respectively, R represents the reflectivity of both mirrors, δ is the phase difference between the reflected lights of the first and second surfaces, and θ is defined as $\delta/2$. The absorption of the modulator material is neglected in this study. Practically, δ or θ can be scanned using the increment of the incident laser wavelength. Figure 2 illustrates that when a reference level is selected, the laser wavelength is locked to the intersection of the transmitted resonance peak and the reference level. The slope $T'(\theta)$ of the transmitted intensity $T(\theta)$ at this intersection determines the sensor sensitivity. The optimal sensitivity occurs where the slope is largest. The optimal sensitivity can be found if the second derivative $T''(\theta)$ is zero. From Eq. (1),

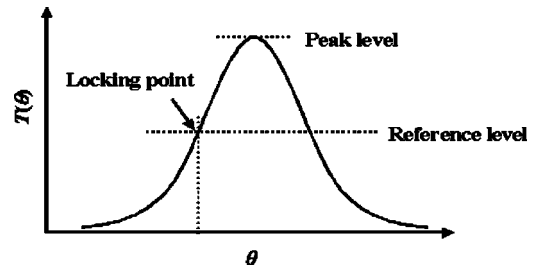


FIG. 2. Lock the wavelength of a laser to one side of the resonance of a Fabry-Perot cavity.

$$T''(\theta) = 2(1-R)^2[(1-R)^2 + 4R \sin^2(\theta)]^{-3} \times (8R \sin \theta \cos \theta)^2 - (1-R)^2[(1-R)^2 + 4R \sin^2 \theta]^{-2} 8R(\cos^2 \theta - \sin^2 \theta) = 0. \quad (2)$$

Consequently, the relation between θ and the reflectivity R for optimal sensitivity can be obtained from Eq. (2),

$$\sin^2 \theta = \frac{(1-R)^2 + 6R - \sqrt{[(1-R)^2 + 6R]^2 - 8R(1-R)}}{8R}. \quad (3)$$

From Eq. (3), the point on $T(\theta)$ with the optimal sensitivity is determined by the reflectivity of cavity mirrors.

Three Fabry-Perot cavities are used to compare the theoretical and experimental optimal sensitivity point of the cavity resonance. The reflectivity of the mirrors of the cavities is 4%, 50%, and 87% at 657 nm wavelength, and the mirror spacing is 11, 3, and 22 mm, respectively. The resonance of each cavity is scanned by the laser wavelength of the same ECDL we used in the experiment of the sensor with bulk modulator and cavity. The resonance signals are recorded and use the recorded signal to calculate the optimal sensitivity point. The best sensitivity point for different reflectivities of the cavity is shown in Fig. 3. In Fig. 3, the locking point of the maximal slope is usually located at about 75% of the top level of the resonance when the reflectivity of the Fabry-Perot cavity mirrors exceeds 85%. The point moves to a higher level when the reflectivity decreases. Figure 4 compares the slope at optimal sensitivity point to the point at half of the resonance top level at different cavity mirror reflectivity. When the reflectivity of the cavity mirrors is beyond 60%, the slope at the optimal sensitivity point is about 30% higher than that of the point at half of the peak level.

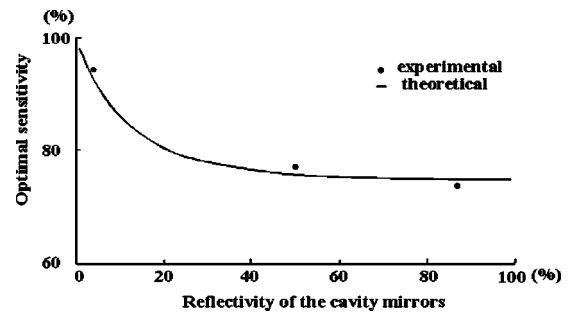


FIG. 3. Optimal sensitivity point vs the reflectivity of the etalon mirrors.

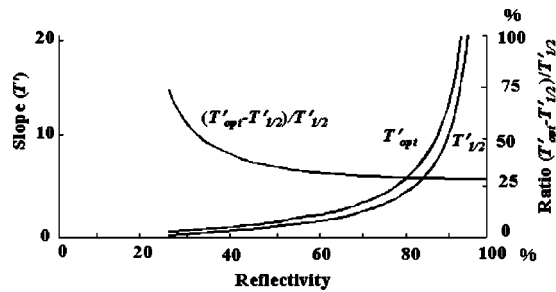


FIG. 4. Comparison of the slope at the optimal sensitivity point and the half height point.

When the reference level for locking the laser wavelength is set to 75% of the top level of the resonance, the power modulation is around 25% of the total output power from the cavity when a 1 V_{p-p}, 1 kHz signal is added to the modulator electrodes. The result resembles that of a Mach-Zender interferometer EOM sensor. The frequency response of the sensor produced by a bulk phase modulator and a cavity was tested. The sensitivity drops when the modulating frequency is beyond 3 MHz, the frequency could be the up-limit of the frequency bandwidth of the detector used in this work.

The sensitivity of a field sensor built by bulk modulator can be very similar to that of a Mach-Zender interferometer type sensor if the sensitivity of the bulk type sensor is enhanced by a Fabry-Perot cavity, and the sensor works on the optimal sensitivity point of the cavity resonance. Using a high Finesse cavity the sensor could achieve even higher sensitivity, but the signal noise induced by the intrinsic phase noise of the diode laser usually cancels out the efforts done on the improvement of the sensor sensitivity. Another problem occurs when the modulating frequency is below 60 Hz. The noise from turbulence of the air between the cavity mir-

rors and mirror vibration is usually mixed with measuring signals. Future work on improving the performance will focus on using a robust structure to isolate the cavity space from the environment and transmit the light via an optical fiber and not through free space. For instance, the cavity reflective mirrors are coated on the optical input and output surfaces of the bulk phase modulator. Following those improvements, the good sensitivity and resistance to electrical shock make the sensor produced by a bulk modulator and a cavity a promising instrument for surveying electrical fields around high voltage systems.

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