Development of Optical Voltage Transducer Based on Dual-Mode Highly Elliptical-Core Polarization Maintenance Fiber

Wei-Hong Bi, Feng Liu, and Xuan Guo

Abstract—This paper describes an optical voltage transducer (OVT) for the 35 kV electric power system based on modular interference in dual-mode highly elliptical-core polarization maintenance fiber (E-Core PMF). The temperature and environmental perturbation can be compensated automatically. In the scheme, a quartz crystal cylinder wrapped with highly elliptical-core fiber plays the role of voltage sensor head. The two interference output lobes’ intensity from the E-core PMF is modulated with the converse piezoelectric effect of quartz crystal. A PZT wrapped with E-core PMF at ground potential serves as the static modular phase difference control and temperature compensation unit. The experiment results indicate that the OVT designed in this paper has satisfying performance and could successfully rejects the temperature perturbation.

Index Terms—Converse piezoelectric effect, dual-mode fiber, modular interference, optical voltage transducer, quartz crystal, temperature compensation.

1. Introduction

Optical voltage transducer (OVT) technology offers an attractive alternative to conventional instrumentation transformer technologies, e.g., inductive voltage transformers and capacitive voltage transformers. Following in the footsteps of their already successful and proven optical fiber sensors, OVT offers several advantages over conventional transformers for measuring voltage such as small size, light weight, wide bandwidth, and large dynamic range. And, the use of optical fiber to sense voltage and transmit data in high voltage environment ensures galvanic isolation of the observer and immunity of the measurement to electromagnetic interference. The electro-optic effect of Pockels crystal is the most prevalent scheme in many previous investigations. However, it has the disadvantage of susceptible to environment perturbation and must be very carefully when assembling it\(^1\)-\(^3\).

Dual-mode fiber sensors are very attractive for the detection of strain of smart structures or piezoelectric and magnetostrictive transducers\(^4\)-\(^5\). For a large range of wavelengths, elliptical-core fibers exclusively support the fundamental \(LP_{01}\) and even \(LP_{11}\) spatial modes with eigen-polarizations parallel to the major or minor core axes. Applied strain alters the differential phase between the two modes and gives rise to a corresponding variation in the double-lobed modal interference pattern. The azimuthal orientation of the interference pattern is stable, as determined by the orientation of the fiber core, which causes the detection of the optical far-field at the fiber end straightforward. Compared to fiber Mach-Zehnder or Michelson interferometers, dual-mode fiber sensors are simpler for no separate reference arm and fiber couplers are needed, and they are unsusceptible to environmental perturbation\(^6\)-\(^8\).

In previous report, a voltage transducer scheme of two dual-mode fibers in tandem act as unbalanced sensor and recovery interferometers has shown the feasibility and advantage of modular interference\(^9\)-\(^10\). While with white light interference technology, the fiber length and offset splice of different fibers must be adjusted carefully. And it is very complicated in large number of manufacture.

In this paper, we present a simple implementation scheme of fiber optic high voltage transducer with automatic temperature compensation ability. The high voltage transducer is based on the modular interference in E-core PMF and converse piezoelectric effect in quartz. Here an ac high voltage produces an alternating piezoelectric deformation of a cylinder-shaped transducer quartz crystal that is sensed by an E-core PMF wound on the circumferential crystal surface. Deformation of the quartz crystal modulates the phase difference of \(LP_{01}\) and even \(LP_{11}\) in E-core PMF, and as a result, output interference two-lobe intensity distribution pattern will exchange with each other. And the ac high voltage can be decided by Two PINs detecting the two-lobe intensity. As an important part,
a PZT wound with E-core PMF serves as static modular phase difference adjusting and temperature compensation device.

2. Modular Interference in E-Core PMF

According to classical fiber optic theory, if a step-index circular core fiber is operated at a wavelength shorter than its single mode wavelength, the first two linearly polarized modes, i.e., $LP_{01}$ and $LP_{11}$ modes, can propagate through the fiber. Two-lobe pattern can be obtained in the far field at the output of the fiber and the oscillation of the intensity distribution between the lobes can be used to sense strain.

However, the four eigen-modes of $LP_{11}$ mode are almost degenerated in step-index circular core fiber. This leads to instability of the mode pattern. The use of highly elliptical-core polarization maintenance fiber has been shown to remedy this situation. Since the circular symmetry of the fiber has been eliminated, only two second-order modes, even $LP_{11}$ modes, are guided by the E-core PMF fibers. The intensity distribution pattern is stable and practical operation of a sensor system is possible. When the $LP_{01}$ and even $LP_{11}$ modes are excited equally in E-core PMF, the output radiation pattern will be a superposition of the contributions from the two modes and a function of the phase difference between them.

The electromagnetic field descriptions for the two linearly polarized modes in E-core PMF can be combined to derive a 3D intensity distribution at the output end of the fiber. Assuming the beam of light propagates through the E-core PMF is Gauss style, $W_x$ and $W_y$ are radius of $x$ and $y$ coordinate correspondingly when the light power attenuates to its $1/e^2$. Then the electric field expression of $LP_{01}$ and even $LP_{11}(LP_{11}^e)$ modes are described by (11):

$$E_{LP_{01}}(x,y) = \frac{Z_0}{n_i} \frac{2}{\pi W_x W_y} \left[ \frac{x^2}{W_x^2} + \frac{y^2}{W_y^2} \right]^{\frac{1}{2}} \exp \left\{ -\frac{1}{2} \left( \frac{x^2}{W_x^2} + \frac{y^2}{W_y^2} \right) \right\}$$

$$E_{LP_{11}}(x,y) = \frac{Z_0}{n_i} \frac{4}{\pi W_x W_y} \frac{x}{W_x} \exp \left\{ -\frac{1}{2} \left( \frac{x^2}{W_x^2} + \frac{y^2}{W_y^2} \right) \right\}$$

where $Z_0$ is the impedance of the vacuum, $n_i$ is the refractive index of the core, $x$ and $y$ are parameters of Descartes coordinate system. If the two modes have the equal intensity and same polarization direction at the output end of the fiber, the output interference intensity can be expressed as

$$I = |E(x,y)|^2 = |E_{LP_{01}}(x,y) + E_{LP_{11}^e}(x,y) \exp(i\Delta\phi)|^2$$

where $I$ is the interference output intensity and $\Delta\phi$ is the phase difference of two modes after propagating through fibers. Fig. 1 shows the intensity distribution pattern at different $\Delta\phi$ (without losing the universality, we let $W_x/W_y = 1.4$). When $\Delta\phi$ changes from 0 to $\pi$, the intensity of two lobe oscillates on time. And it has the similar phenomena when $\Delta\phi$ changes from $\pi$ to $2\pi$.

![Fig. 1. The relationship between far field intensity distribution and modular phase difference $\Delta\phi$. (a) $\Delta\phi = 0^\circ$, (b) $\Delta\phi = 90^\circ$, (c) $\Delta\phi = 180^\circ$, and (d) $\Delta\phi = 270^\circ$.](image)

3. Transducer Principle

The transducer setup is schematically illustrated in Fig. 2. The light from the laser source is transmitted by a single mode fiber to the fiber-optic polarizer. The linearly polarized output subsequently travels into a piece of E-core PMF with the polarization parallel to the major axis of it. One part of the E-core PMF is wound on a PZT tube as static modular phase difference controller and the other is wound on three quartz crystal cylinders which sandwiched in four metal electrodes as sensor head. The far-field modal interference pattern at the output end of the E-core PMF is monitored by two p-i-n photodiodes.

![Fig. 2. Setup of the fiber-optic transducer.](image)
The configuration of quartz crystal cylinder is illustrated in Fig. 3. The longitudinal axis coincides with a two-fold crystal axis (x-direction). An alternating voltage applied along x produces an alternating piezoelectric strain along y, hence a modulation of the transducer’s circumferential length l. The relative length change is given by \[ \Delta l = -\frac{1}{2} \pi d_{11} \frac{U}{h} dl \] (4)

where \( U \) is the high voltage applied on crystal along x, \( h \) is the height of quartz crystal, \( d \) is the diameter of quartz crystal, and \( d_{11} = 2.31 \times 10^{-12} \) m/V is the piezoelectric coefficient. Thus the variety of modal phase difference \( \Delta \phi \) is

\[ \delta \phi = -\frac{\pi^2 N}{\Delta L_{2x}} \frac{U}{h} d \] (5)

where \( N \) is the fiber-optic loops number wound on quartz crystal, \( \Delta L_{2x} \) is the modal beat length of \( LP_{01} \) and even \( LP_{11} \) modes in E-core PMF.

Fig. 4. The propagation characteristics of several low order modes in E-core PMF.

Fig. 4 is the plot of normalized propagation constant \( \beta / k_0 \) versus normalized frequency \( V \) of several low order modes in the E-core PMF from IVG. Fig. 4 shows the E-core PMF can only propagate \( LP_{01} \) and even \( LP_{11} \) modes if a 980 nm laser source is focused on the fiber end.

3. Propagation Character of E-Core PMF

In practice, a suitable range of operating wavelengths must be chosen for implementing modular interference fiber sensors. In this section, we calculate the propagation characteristics of an E-core PMF from IVG Company with effective refractive method.

Fig. 5. Experiment result from oscillograph: (a) signals after BPF and (b) signal of output voltage.

Fig. 6 shows the relationship of output voltage from fiber-optic transducer and high voltage applied on the transducer.

5. Conclusion

We have adopted the modular interference technology to employ a fiber-optic high voltage transducer. And it has the ability for measuring voltage as high as 50 kV. The experiment results obtained demonstrate that with suitable
signal process method, a very simple scheme of fiber-optic high voltage transducer can obtain satisfying accuracy and stability. Comparing with some other configurations of sensors based on modular interference, this scheme do not need complicated optic devices and skillful offset fused splices for several individual piece of different PMF.

With the advantages of simple structure, easy assembly, and stability of long period, OVTs based on modular interference theory have many merits over their conventional counterparts.

References


Wei-Hong Bi was born in Hebei Province, China, in 1960. She received the B.S. degree from the Institute of Northeast Heavy-Duty Machine, Harbin, in 1982 and the Ph.D. degree from the Harbin Institute of Technology in 2003. She is currently a professor of Yanshan University. Her research interests include optic-fiber sensors and optoelectronic instrument.

Feng Liu, was born in Jilin Province, China, in 1976. He received the B.S., M.S., and the Ph.D. degrees in 1999, 2003, and 2008, respectively, all from Yanshan University. He is currently a lecturer with Yanshan University. His research interests include optical high voltage and large current transducers.

Xuan Guo was born in Hebei Province, China, in 1981. She received the B.S. and M.S. degrees in 2003 and 2006, both from Yanshan University. She is currently pursuing the Ph.D. degree with the Department of Information Science and Engineering, Yanshan University. Her research interests include optic crystal fiber sensors.