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Influence of surface errors on the performance of EFPI based on GRIN lenses

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ABSTRACT

The graded index (GRIN) lens reduces the divergence angle of the beam exiting from the lead-in optical fiber, which results in the increasing of F–P cavity mirror areas. Surface errors of the increased mirrors cannot be ignored due to the machining tolerance. The influence of surface errors on the performance of the fiber extrinsic Fabry–Perot interferometer (EFPI) is researched. Theoretical analysis and numerical simulation results demonstrate that surface errors will diminish the interference contrast. The larger the surface error, the smaller the interference contrast will become. The results will contribute to the design of an EFPI with a certain interference contrast.

1. Introduction

Optical fiber EFPI have many advantages, such as immunity to electromagnetic interference (EMI), high resolution, small size, and structural ruggedness, so in recent years they are used to measure the parameters of pressure [1,2], strain [3], temperature [4], displacement [5], ultrasound [6], magnetic field [7], partial discharge [8], and refractive index [9]. A simple method to fabricate an EFPI sensor is packaging two cleaved optical fibers into a capillary tube, leaving an air gap between the two fiber endfaces. Reflections of light from the two cleaved fiber surfaces form an interference signal that can be recorded and processed to find the cavity length. When used as a sensor, the cavity length changes as a function of the parameters to be measured.

Although the EFPI sensor fabricated by using two cleaved optical fibers is straightforward and cost effective, it has the interference contrast decreasing rapidly as cavity length increases due to the large divergence (about 6° for single mode fiber (SMF)) of the beam exiting from the lead-in SMF. The decreasing interference contrast could result in a reduced SNR and decreased measurement accuracy [10]. Thus, the EFPI is restricted to the applications where a long initial cavity length or large dynamic range is required.

To improve the interference contrast in a long cavity EFPI, Gangopadhyay et al. fabricated an EFPI using a coated GRIN lens pigtailed to the lead-in optical fiber [11]. The use of a GRIN lens reduces the divergence angle of the beam exiting from the lead-in optical fiber. However, it also increases the area of the cavity mirrors from about 10 μm to about 500 μm. For the mirror less than 10 μm, surface errors can be ignored due to its small area. Yet, for the mirror which is large enough to 500 μm, surface errors cannot be ignored. Machining tolerance determines that mirror surface errors are inevitable. In addition, complicated assembly of GRIN lens has a strong possibility to result in surface errors. When the surface errors increase to sum-μm level, their influence on the interference contrast is visible. Hence, when we design an EFPI with a certain interference contrast, we should add the consideration of the influence of mirror surface errors. To the best of our knowledge, up to now, all research about the design of an EFPI based on GRIN lenses did not considered the influence of cavity surface errors.

In this paper, assuming that the beam width does not change after multiple reflections in the F–P cavity, the interference contrast as function of surface errors is researched. This paper has the following outline. In Section 2, the dependence of the interference contrast on surface errors is analyzed. Section 3 is devoted to numerical analysis. Section 4 summarizes our results.

2. Performance of EFPI for the F–P cavity with surface errors

A GRIN lens, as shown in Fig. 1, can function as a collimator which expands the beam exiting from a SMF. The expanded beam is still a Gaussian beam with a cross-sectional intensity distribution of a

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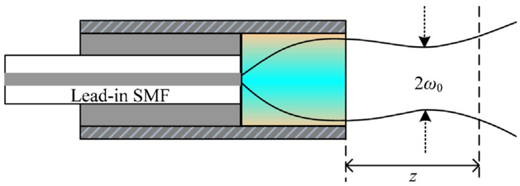

Fig. 1. Graded index (GRIN) lens functioned as a collimator.

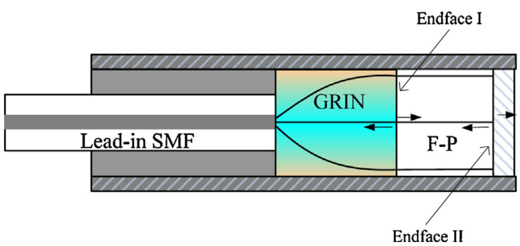

Fig. 2. EFPI based on GRIN.

Gaussian profile. The cross-sectional intensity profile of the light at the axis distance z from the endface of the GRIN lens can be approximated as

$$I(r,\varphi,z)=\frac{2P_0}{\pi\omega(z)^2}\exp\left(-\frac{2r^2}{\omega(z)^2}\right), \tag{1}$$

where (r, φ) is the position in cross-section; P_0 is the total power of the light; and $\omega(z)$ is the beam radius at the axial position z, at which the light intensity reduces to $1/e^2$ of its maximum intensity.

The beam radius of the Gaussian beam varies along the propagation direction according to the following equation:

$$\omega(z)=\omega_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}, \tag{2}$$

$$z_R=\frac{\pi\omega_0^2}{\lambda}, \tag{3}$$

where z_R is the Rayleigh length, and ω_0 is the beam radius at the beam waist where the beam radius is at its minimum, which determines the divergence angle θ by the following equation:

$$\theta=\frac{\lambda}{\pi\omega_0}, \tag{4}$$

Eq. (2) shows that if $z \ll z_R$, $\omega(z)\approx\omega_0$. According to the reverse relation between the divergence angle θ and beam waist ω_0 shown in Eq. (4), we can conclude that the smaller the divergence angle, the longer the distance z which satisfies the relationship of $\omega(z)\approx\omega_0$. For the beam divergence θ which is small enough to 0.25°, the distance z can increases to 2 mm.

The EFPI based on a GRIN lens is shown in Fig. 2. To simplify the problem, we assume that the beam divergence angle is so small that the change of the beam width after multiple reflections can be neglected. If the two endface mirrors of F–P cavity are parallel but have the surface error of $\Phi(r,\varphi)$, the air-gapped EFPI can be modeled using the multi-beam interference equation and the optical intensity of the reflected light at the position (r,φ) is

$$I(L,\Phi)=\frac{2P_0}{\pi\omega_0^2}\exp\left(-\frac{2r^2}{\omega_0^2}\right)\frac{R_1+R_2-2\sqrt{R_1R_2}\cos(4\pi((L+\Phi(r,\varphi))/\lambda))}{1+R_1R_2-2\sqrt{R_1R_2}\cos(4\pi((L+\Phi(r,\varphi))/\lambda))}. \tag{5}$$

Here R_1 and R_2 are the reflectivity of the two mirrors, respectively; L is the cavity length; and λ is the optical wavelength in a vacuum.

Surface errors can be expressed by Zernike polynomials as follows:

$$\Phi(r,\varphi)=\sum_{i=0}^{N}A_iZ_i\left(\frac{r}{a,\varphi}\right), \tag{6}$$

where a is the radius of the GRIN lens, and $Z_i(r/a,\varphi)$ are Zernike polynomials which are a set of polynomials defined on a unit circle; A_i is the Zernike polynomial coefficient; and the index j is a mode ordering number. For the primary surface errors, Zernike polynomials are

$$\text{Tilt}:\quad\begin{cases}Z_1=r\cos\varphi/a,\\ Z_2=r\sin\varphi/a,\end{cases} \tag{7}$$

$$\text{Defocus}:\quad Z_3=\frac{2r^2}{a^2}-1, \tag{8}$$

$$\text{Astigmatism}:\quad\begin{cases}Z_4=r^2/a^2,\\ Z_5=r^2\sin\varphi\cos\varphi/a^2,\end{cases} \tag{9}$$

$$\text{Coma}:\quad\begin{cases}Z_6=(3r^2-2)r\cos\varphi/a^3,\\ Z_7=(3r^2-2)r\sin\varphi/a^3,\end{cases} \tag{10}$$

$$\text{Spherical}:\quad Z_8=\frac{6r^4}{a^4}+\frac{6r^2}{a^2}-1. \tag{11}$$

The optical power $P(L,\Phi)$ of interference signal coupled into the lead-in fiber can be calculated by integrating the light intensity within the mirror area of F–P cavity, which is given by

$$P(L,\Phi)=\int_{r=0}^{a}\int_{\varphi=0}^{2\pi}I(L,\Phi)r\,dr\,d\varphi. \tag{12}$$

Substituting Eq. (5) into Eq. (12), we get

$$P(L,\Phi)=\frac{2P_0}{\pi\omega_0^2}\int_{r=0}^{a}\int_{\varphi=0}^{2\pi}\exp\left(-2\frac{r^2}{\omega_0^2}\right)\frac{R_1+R_2-2\sqrt{R_1R_2}\cos(4\pi((L+\Phi(r,\varphi))/\lambda))}{1+R_1R_2-2\sqrt{R_1R_2}\cos(4\pi((L+\Phi(r,\varphi))/\lambda))}r\,dr\,d\varphi. \tag{13}$$

Eq. (13) can be rewritten as

$$P(L,\Phi)=\int_{\Phi_{\min}}^{\Phi_{\max}}\rho(\Phi)f(L,\Phi)\,d\Phi, \tag{14}$$

$$\int_{\Phi_{\min}}^{\Phi_{\max}}\rho(\Phi)\,d\Phi=2\pi\omega_0^2P_0, \tag{15}$$

$$f(L,\Phi)=\frac{R_1+R_2-2\sqrt{R_1R_2}\;\cos(4\pi(L+\Phi)/\lambda)}{1+R_1R_2-2\sqrt{R_1R_2}\;\cos(4\pi(L+\Phi)/\lambda)}. \tag{16}$$

Here $\Phi_{\max}$ and $\Phi_{\min}$ are the peak and valley of surface error $\Phi(r,\varphi)$, respectively; $\rho(\Phi)$ denotes the weight factor of interference signal for cavity length of $L+\Phi$, which is determined by the profile of $\Phi(r,\varphi)$ and the optical intensity distribution of $I(r,\varphi)$. Eq. (16) shows that the optical power of interference signal is the sum of the optical intensity for different cavity length $L+\Phi$ with different weight factors $\rho(\Phi)$.

Using the basic definition of integral, Eq. (16) can be written as

$$P(L,\Phi)=\sum_{k=M}^{N}\rho(k\cdot\Delta\Phi)f(L,k\cdot\Delta\Phi), \tag{17}$$

where $\Delta\Phi\to0$, k is an integer, $N=\Phi_{\max}/\Delta\Phi$, and $M=\Phi_{\min}/\Delta\Phi$.