Nonlinear strain response of two-mode fiber-optic interferometer

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Experimental and theoretical investigation of a nonlinear response of a two-mode fiber interferometer to axial strain is described. It is discovered that the nonlinearity dramatically increases as the wavelength approaches the cutoff wavelength of the second-order mode (LP_{11}). © 1996 Optical Society of America

Two-mode fiber-optic interferometers have advantages over conventional two-arm interferometers because of their simplicity and stability, making them attractive for sensing of strain,[1–3] stress,[4] temperature,[2] and voltage.[5] The interferometer is based on the modal interference between the LP_{01} and the LP_{11} modes propagating in a two-mode fiber. Previous studies have assumed that the differential phase shift between the two modes has a linear relationship with the perturbations (strain, temperature, etc.) applied to the two-mode fiber. In this Letter we report an observation and analyses of an extraordinary behavior in a two-mode fiber-optic interferometer under axial strain. The key finding is the nonlinear response of the differential phase shift between the two spatial modes (LP_{01} and LP_{11}) to the fiber elongation, especially when the optical wavelength is near the cutoff wavelength (λ_c) of the LP_{11} mode. The phenomenon may have significant implications in the application of two-mode fiber-optic interferometers to strain sensing. In some case it should be carefully avoided, and in others it may be advantageously used for new types of sensors. We present a theoretical explanation of the observed nonlinear response. We also report the observation of a large difference in λ_c for two eigenpolarization components of a high-birefringence fiber (bowtie fiber) with an elliptical core, similar to results reported earlier[6,7] but with a much larger difference of 35 nm.

Figure 1 shows the experimental setup used for the measurement of the strain effect on the phase difference between the LP_{01} and the LP_{11} modes in the two-mode fiber-optic interferometer. The fiber had a highly elliptical core and dimension of approximately 7 μm × 4 μm and had bowtie stress members along the minor axis of the core. The cutoff wavelength of the second-order mode (LP_{11}^{even}), measured by using the spectral loss measurement method,[8] was ~ 670 nm for the polarization along the major axis (x polarization) and ~ 705 nm for the polarization along the minor axis (y polarization) of the core. By using the prism output coupling technique,[9] we measured the beat length between the LP_{01} and LP_{11} modes at the 633-nm wavelength, which was ~215 μm for the x polarization and ~205 μm for the y polarization. The total length of the fiber was 150 cm, and the elongated section was 48 cm long. Lasers with various wavelengths were used as the optical source, and approximately equal intensity was excited in the two spatial modes. One of the eigenpolarization modes was excited at a time. We measured the phase shift by detecting the optical intensity in one half of the far-field radiation pattern.[1]

Figure 2(a) shows experimental results of the optical output intensity versus elongated length when the input polarization is parallel to the x axis. At the wavelengths of 543 and 578 nm, which are far from the cutoff wavelength ($\lambda_c \simeq 670$ nm), the periodic fringe shift indicates an almost linear relationship between the differential phase shift and the elongated length. At the wavelength of 638 nm, the nonlinear response was clearly observed, in that the differential phase shift per unit elongation decreased as the fiber elongation increased. In this case, the elongation length needed for 2π differential phase shift was also much larger than that for shorter wavelengths. Figure 2(b) shows the experimental results for the y-polarization input with the cutoff wavelength of ~ 705 nm. The interferometer output shows behavior similar to the results for the x polarization.

To understand the nonlinear response of the two-mode fiber-optic interferometer to strain, we have calculated the effect of axial strain on the phase difference ϕ between the LP_{01} and LP_{11} modes. In the following analysis, an elliptical core fiber with a step-index profile is assumed. The phase difference accumulated in the two-mode fiber-optic interferometer can be represented as

$$\phi = \frac{2\pi l}{L_B}, \tag{1}$$

where l is the fiber length in the interferometer and $L_B = 2\pi/(\beta_{01} - \beta_{11})$ is the beat length between the

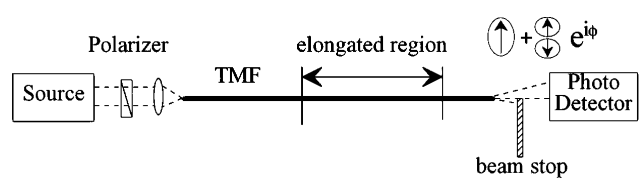

Fig. 1. Experimental setup for measuring the strain response of a two-mode fiber-optic interferometer. TMF, two-mode fiber.

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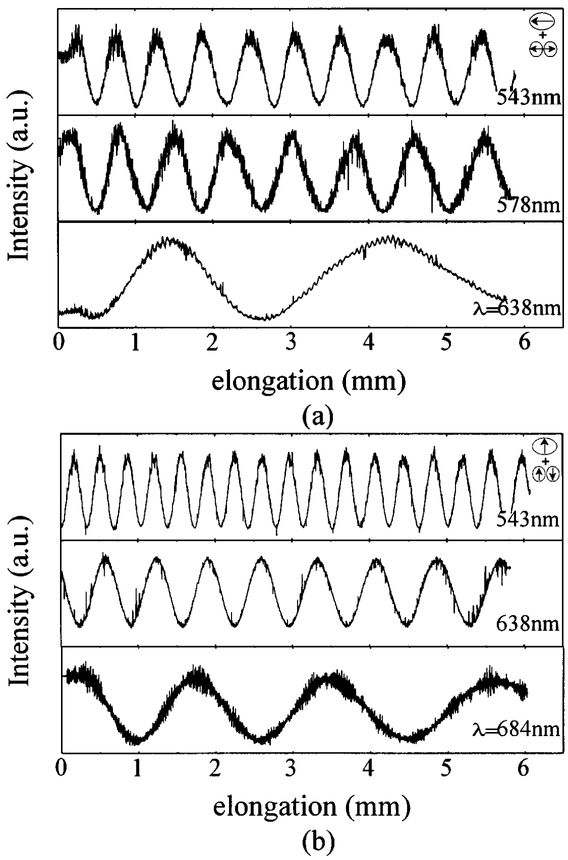

Fig. 2. Interferometer output intensity versus elongation length δl for (a) x polarization and (b) y polarization.

two modes. Here β_{01} and β_{11} are the propagation constants of the LP_{01} and the LP_{11} modes, respectively. When the weakly guiding approximation is applied, the beat length can be expressed as[1]

$$L_B = 2\pi a\sqrt{\frac{2}{\Delta}}\, f(V, \epsilon)\,. \tag{2}$$

Here a is the semimajor axis of the fiber, $\Delta = ({n_1}^2 - {n_2}^2)/(2{n_1}^2)$ is the normalized refractive-index difference, where n_1 and n_2 are the refractive indices of the core and the cladding, respectively. ϵ = (minor axis)/(major axis) is the aspect ratio of the core. $V = 2\pi a n_1\sqrt{2\Delta}/\lambda$ is the normalized frequency, where λ is the optical wavelength in vacuum. The function $f(V, \epsilon)$ is the normalized beat length, which depends on V and ϵ only in the weakly guiding approximation.

As the fiber is stretched by $\delta l(\delta l \ll l)$, the differential phase shift between the two spatial modes can be calculated by using the Taylor expansion of Eq. (1):

$$\frac{\delta\phi}{\delta l} \simeq \frac{2\pi}{L_{B_0}}\left[1 - \frac{l}{L_B}\frac{\delta L_B}{\delta l}\bigg|_{L_B = L_{B_0}} - \frac{1}{2}\,\delta l\,\frac{\delta}{\delta l} \times \left(\frac{l}{L_B}\frac{\delta L_B}{\delta l}\right)\bigg|_{L_B = L_{B_0}} - \frac{1}{2}\,\delta l\left(1 - \frac{l}{L_B}\frac{\delta L_B}{\delta l}\right) \times \frac{1}{L_B}\frac{\delta L_B}{\delta l}\bigg|_{L_B = L_{B_0}}\right], \tag{3}$$

where L_{B_0} is the initial value of L_B. This equation can be expressed in the following form by using new functions $A(V)$ and $B(V)$ for a fused-silica fiber that has a refractive index of 1.46, Poisson's ratio (σ) of 0.17, and strain-optic coefficients of $p_{11} = 0.12$ and $p_{12} = 0.27$, respectively:

$$\frac{\delta\phi}{\delta l} = \frac{2\pi}{L_{B_0}}\, A(V_0)\left[1 - B(V_0)\,\frac{\delta l}{l_0}\right],$$

where

$$A(V) \simeq 0.953 + 0.605\,\frac{V}{f(V, \epsilon)}\,\frac{\delta f(V, \epsilon)}{\delta V}\,,$$

$$B(V) \simeq \frac{1}{2}\left[0.605\,\frac{V}{A(V)}\,\frac{\delta A(V)}{\delta V} + 1 - A(V)\right]. \tag{4}$$

Here l_0 and V_0 are the initial values of l and V, respectively. The function $A(V)$ represents the proportionality constant of the differential phase shift with respect to the elongated length of the fiber. $B(V)$ is responsible for the nonlinear relationship between the differential phase shift and the elongated length. If $A(V) = 1$ and $B(V) = 0$, then $\delta\phi = 2\pi$ for $\delta l = L_{B_0}$. We have calculated the $A(V)$ and $B(V)$ for an elliptical core fiber with a 4/7 aspect ratio of the core, using the point-matching method.[10,11] Note that in the above analysis we neglected the polarization dependence by not taking into account the z component of the electric field of the modes.[12] Therefore Eq. (4) cannot explain the large difference in the strain effect for the two polarization components observed in the experiment. However, Eq. (4) explains the origin of the nonlinear strain response that is the key subject discussed in this Letter. For a better match between the theoretical and the experimental analyses, we need to know accurate optical, geometric, and stress parameters of the fiber used in this experiment, which has a very complicated structure with bowtie stress members. Figure 3 shows $A(V)$ and $B(V)$ as functions of the normalized frequency. Note that the LP_{11} mode cutoff frequency calibrated with the major axis becomes $V_c = 2.809$. Far from the cutoff frequency, $A(V)$ is close to unity and $B(V)$ becomes small enough that the elongation length needed to induce 2π differential phase shift between the two spatial modes is close to a beat length with an almost linear response. As the normalized frequency approaches V_c, $A(V)$ converges to zero and $B(V)$ becomes large. This means that the differential phase shift per unit of elongation length becomes significantly smaller and the nonlinearity becomes larger, as

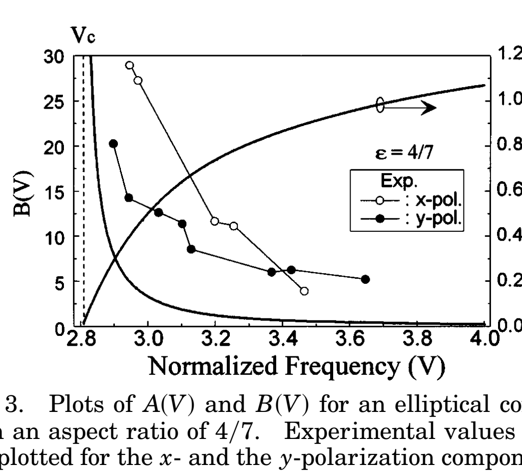

Fig. 3. Plots of $A(V)$ and $B(V)$ for an elliptical core fiber with an aspect ratio of 4/7. Experimental values of $B(V)$ are plotted for the x- and the y-polarization components.

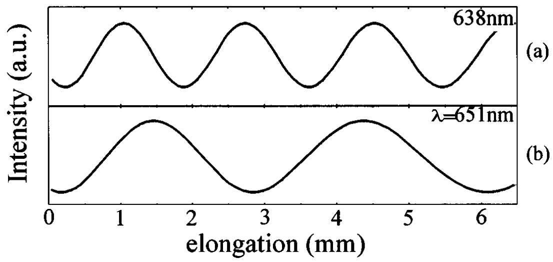

Fig. 4. Calculated results of the interferometer output intensity versus elongation for an elliptical core fiber with a 7 μm $\times$ 4 μm core and a cutoff wavelength of 670 nm.

has been observed in our experiments. For a comparison, the experimental values of $B(V)$ for two eigenpolarization states are plotted in the figure. The values are estimated from experimental curves such as those shown in Fig. 2, obtained at various wavelengths. The experimental results show much larger values compared with those predicted from Eq. (4).

To show more clearly the nonlinear behavior under study, a numerical simulation was attempted by use of Eq. (4) and the experimental fiber parameters of $\lambda_c = 670$ nm and core dimensions 7 μm $\times$ 4 μm. In this case L_B is calculated from Eq. (2) to be 578 μm, which is much larger than the experimental values of $\sim$200 μm. Figure 4(a) shows the numerical simulation for the output intensity versus the elongation length at $\lambda = 638$ nm. The result shows a nonlinear response, but with a smaller nonlinearity and a greater strain sensitivity compared with the experimental result shown in Fig. 2(a). A simulated result similar to the experimental one could be obtained when we used the operating wavelength of 651 nm as shown in Fig. 4(b). We believe that the relatively large discrepancy between theoretical and experimental results originates from the simplified theoretical model with a step-index profile and zero stress field in the fiber. To reduce the discrepancy, one has to use the exact index profile and take into account the effects of the z component of the electric field,[12] electric polarization-induced charge at the core–cladding boundary,[13] and particularly the change in the stress field.[14] This is beyond the scope of this Letter. The large difference between the two polarization components is believed to come from a similar origin, part of which has been discussed elsewhere.[12] In spite of the quantitative differences, the theoretical analysis provides a correct nonlinear behavior near λ_c.

In conclusion, we have described the nonlinear response of a two-mode fiber-optic interferometer to strain with experimental results and theoretical analyses. A large nonlinear response was observed when the light source was operated near the cutoff wavelength of the LP_{11} mode. The large polarization dependence of the λ_c and the strain response were also measured for an elliptical core bowtie fiber. These findings will play an important role in applications of two-mode fibers.

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