Investigation of Phase Modulation Sensitivity in Plastic Optical Fiber*

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Abstract The phase modulation within piezoelectric coating PMMA core plastic optical fiber (POF) is demonstrated. RF signals induce strains within fiber core due to electric-mechanic effects in piezoelectric coating, thus the phase of optical signals in fiber is modulated. Compared with conventional glass fiber, PMMA core POF has a phase modulation sensitivity of more than ten times larger.

Keywords Phase modulation; Piezoelectric coating; Plastic fiber; Phase modulation sensitivity
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0 Introduction

Phase modulation within optical fibers are attracting more research due to their wide applications[1,2]. Optical signals propagating within fiber core can be phase modulated by strains, which are induced by piezoelectric coating applied with voltage boundaries, or RF signals. Phase modulation plays an essential role in EM sensing, EMC testing as well as optical signal processing. High phase sensitivity has been achieved employing coated piezoelectric copolymer, vinylidene fluoride/trifluoroethylene, and many works have been done based on experiments, theoretical analysis as well as numerical simulations. Different piezoelectric coatings, such as zinc oxide (ZnO) film[3], VDF/TFE[4], VDF/TrFE[5], have been reported to improve phase sensitivity. However, because silica glass has large Young's modulus, the change of refractive index due to the changes in strain is small. In the case of plastic optical fiber (POF), the situation is different. Its Young's modulus is more than several tens of times smaller than that of glass, and the refractive index changes that can be induced by strains are relatively high. Therefore, it is expected that higher phase sensitivity can be achieved in POF. In addition, POF appears to be viable candidate for many short reach high-speed applications due to many recent advances in the technology. The POF based devices will be compatible with POF links and networks.

In this paper, phase modulation sensitivity in PMMA POF has been analyzed and computed. The phase sensitivity within PMMA POF is 0.5 rad/V/m, compared to that of conventional glass fiber 0.04 rad/V/m, more than ten times of sensitivity has been achieved.

1 Theory

The scheme of POF modulator is shown in Fig. 1. Optical light from laser is phase modulated by POF modulator, which is applied AC voltage upon inner and outer metal electrodes, and then are distributed to the transmission system. Cross section, including POF radius, copolymer jacket thickness and thickness of electrodes, are also demonstrated.

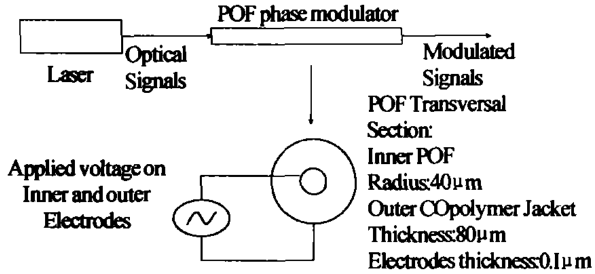

Fig. 1 POF phase modulator and its transversal section

In the electric field environment, the piezoelectric material deforms, and strains are induced within fiber core. Strains contribute to phase shift in two aspects: the change of refractive index, and change of optical fiber length. The piezoelectric coating induced phase shift is as follows[6]

$$\Delta\phi = k_0 nL\{S_3 - \frac{n^2}{2}[P_{11}S_1 + P_{12}S_2 + P_{12}S_3]\} \quad (1)$$

where k_0 is optical wavenumber in vacuum, n is efficient refractive index of optical fiber. S_1, S_2 and S_3 are the induced strains along x, y, z direction; P_{11} and P_{12} are coefficients. Normally, in low frequency range, optical phase shift is mainly caused by the joint effects of axial strain and radial strains. In high frequency, since the length of optical fiber is much longer than axial acoustic wavelength, the net axial strain tends to zero, so that phase shift is induced by radial strains[5]. When $S_3 = 0$ in (1), we get the expression

$$\Delta\phi = -k_0 n^3 L(P_{11} + P_{12})\frac{S_r}{2} \quad (2)$$

here S_r denotes the radial strain.

The displacement in the radial direction U, when denoted in the spatial part, satisfies the equation

$$\frac{d^2U}{dr^2} + \frac{1}{r}\frac{dU}{dr} + \{\omega^2\frac{\rho}{C_{11}} - \frac{1}{r^2}\}U = 0 \quad (3)$$

In each layer, displacement satisfies the above equation, where ρ and C_{11} are density and elastic constant of material of the corresponding layer, respectively.

The result of the above differential equation is combination of two Bessel function, the two unknown

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coefficients are decided by boundary conditions. We assume that the coating/air surface is stress-free, and continuity of displacement and mechanical stress in the fiber/coating surface.

When the displacement in the radial direction is known, the strains can be calculated as

$$S_r = \frac{dU(r)}{dr} \tag{4}$$

2 Results and discussions

Considering boundary conditions $U(0)=0$, stress $\sigma(r=d)=0$, and displacement and stress continuity in the fiber/inner electrode, inner electrode/coating and coating/outer electrode surfaces, we can decide two coefficients in the solution of (3) in each frequency through matrix form equation[5]. Once this has been done, displacement within fiber and copolymer is obtained, and finally, phase shift induced within fiber is determined in (2) by radial strain $S_r(r=0)$.

The frequency response from 500 KHz to 50 MHz is calculated, in which net axial strain tends to be zero, and termed axially constrained. Taking parameters of PMMA plastic fiber in calculation, and the coefficients P_{11} and P_{12} remain the same with those of glass fiber, see table 1, we get some favorable results. As shown in Fig. 2, the resonant peaks occurred in some frequencies, such as 7.3, 19.6, 42.5 MHz at the first, second and fourth resonance, respectively. In the range of 500 KHz up to 6 MHz, the phase sensitivity is rather flat, and smaller compared to those in the resonant peaks. This is due to the anti-resonant phenomenon[4], which can be explained as nearly zero strains are induced in the fiber core and cladding, as shown in Fig. 3(a). The displacement within fiber core is nearly zero, and that in copolymer is 10^{-11}, two orders less than displacements in the resonant peaks at 7.3, 19.6 and 42.5 MHz, as shown in Fig. 3(b), (c) and (d), respectively.

Table 1 Elastic Constants of PMMA, metallic electrodes, copolymer Jacket As Well As Piezoelectric And Dielectric Constants of The Copolymer

PMMA fiber	
Density	$1.19\times10^3 kg/m^3$
Refractive index	1.491
Youngs Modulus	2.4-3.3 GPa
Poisson's ratio	0.35 ~ 0.40
Aluminum (electrode)	
Density	$2.69\times10^3 kg/m^3$
Elastic constants	$C_{11}=1.1\times10^{11} N/m^2$
	$C_{12}=5.81\times10^{10} N/m^2$
Copolymer (jacket)	
Density	$1.89\times10^3 kg/m^3$
Elastic constants	$C_{11}=8.8\times10^9 N/m^2$
	$C_{12}=4.7\times10^9 N/m^2$
Piezoelectric constants	$h_{11}=-9.98\times10^8 N/C$
	$h_{12}, h_{13} \sim 0 N/N$
Poisson's ratio	0.35
Dielectric constant	6.0

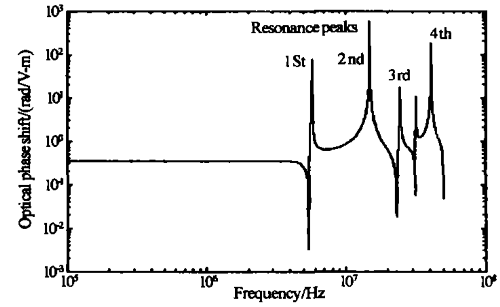

Fig. 2 Optical phase shift in the range of frequency from 10^5 Hz to 10^8 Hz, Resonance peaks are shown

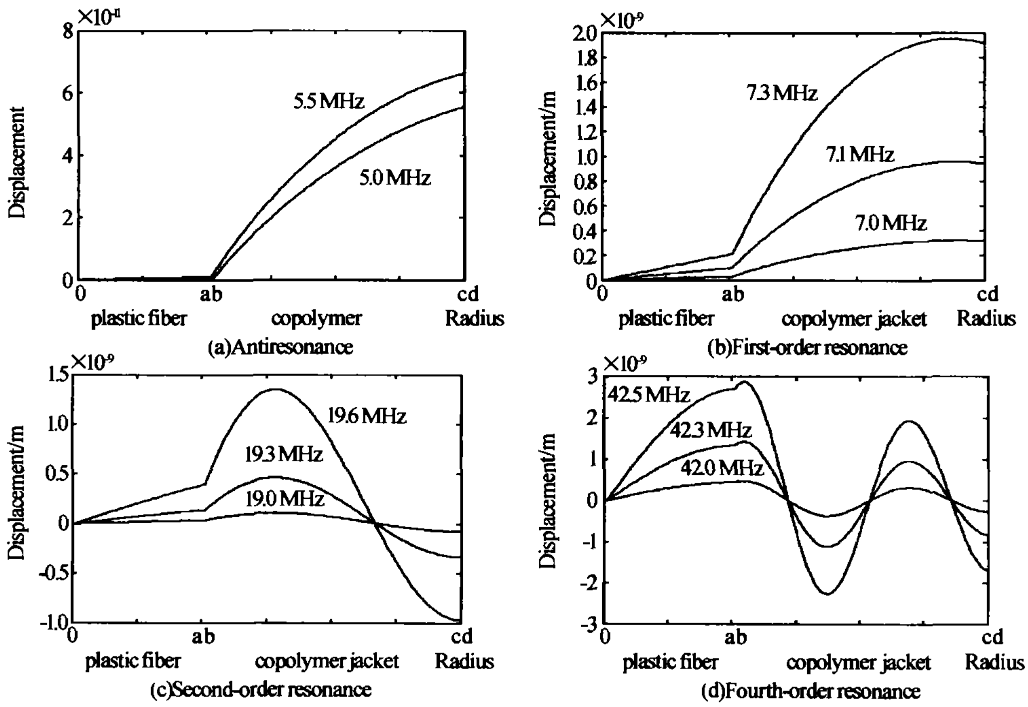

Fig. 3 Radial displacement in the resonance frequency

Higher phase sensitivity is obtained in PMMA core POF, within the whole frequency it has been increased by tenfold than that in glass fiber. In the polymer coated glass fiber, the phase sensitivity is 0.04 rad/V/m, while in PMMA core POF, the phase sensitivity is about 0.50 rad/V/m. Reasonable explanation is that Youngs modulus of POF is about 2.4-3.3 GPa, which is much smaller than that of glass fiber (73 GPa). The resonant frequencies in POF are the same as in glass fiber, and at each resonant frequency, the displacement shapes between them also remain the same, while as for the resonant amplitudes, POF are larger than glass fiber.

3 Conclusion

We have utilized plastic fiber as the substitute for conventional one in optical phase modulation. Higher sensitivity has been obtained, which is more than ten times as large as the silica fiber.

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塑料光纤相位调制灵敏度的研究

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摘 要 研究了压电涂层 PMMA 纤芯塑料光纤中的相位调制．射频信号通过对光纤外层的压电涂层作用，使纤芯中产生应变，从而对光纤中的光信号进行相位调制．数值计算结果表明，与传统的石英光纤相比，PMMA 塑料光纤的相位调制的灵敏度要高数十倍以上．

关键词 相位调制；压电涂层；塑料光纤；相位调制灵敏度

Yuan Yu was born in 1976. He received his M. S. degree from Department of Electrical Engineering, Zhejiang University in 1999. Since 2001, he has been a graduate student in Department of Information and Electronic Engineering, Zhejiang University. In fall semester, 2003, he became a Ph. D. candicate, and his current research interests include microwave photonics and left handed materials.