Second order nonlinearity in doped polymer optical fibre

P. Ji, G.D. Peng and P.L. Chu
Australian Photonics CRC, School of Electrical Engineering & Telecommunications,
University of New South Wales, Sydney, NSW 2052, Australia

Abstract

This paper reports a simple technique to induce second order nonlinearity in doped electro-optic polymer optical fibre through direct electric poling. The nonlinear effect is measured through a simple yet highly accurate and sensitive transverse modulation scheme. Experimental results show that liquid crystal has the highest electro-optic effect among different nonlinear dopants. Some of the applications are briefly discussed.

1. Introduction

Over the past decades, electro-optic polymers (polymer material doped with molecular units with large nonlinear polarisabilities) have attracted more and more interest because of their reasonably high nonlinear effect, high speed, ease of processing and low manufacturing cost compared with conventional crystal devices [1-2]. However, most of the research works were carried out on thin film waveguide structure [3-7], only recently some works have been started on fibre or fibre preform structure [8-9]. Compared to the planar waveguide structure, the polymer optical fibre (POF) device has the advantage of ease of inserting into the optical circuit, and so the insertion loss at the interface is minimised. Making device in fibre structure will also meet the increasing demand as POF technology develops. Our research focuses on polymeric electro-optic device in the fibre structure, which includes the preform structure.

2. Nonlinear electro-optic effect in polymer materials

Electro-optic effect is the linear change in refractive index of a material caused by an applied electric field. The electric field induces a polarisation P in the material:

$$P = \chi_I^{(1)} E_I + \chi_{IJ}^{(2)} E_I E_J + \chi_{IJK}^{(3)} E_I E_J E_K + ...$$

In this formula the χ's are the first, second and third order susceptibilities, E's are the applied electric fields. The electro-optic coefficient is related to the $\chi^{(2)}$ term, where E_I is the applied voltage, E_J is the interacting optical field. Microscopically, $\chi^{(2)}$ is related to the first hyper polarisability of the material, β. Therefore materials with large first hyper polarisability will have large electro-optic coefficient once being poled. However, the electro-optic effect achievable in the doped polymer material is limited by the intermolecular electrostatic interaction [10].

In our experiment, the nonlinear dyes used are: Disperse Red 1 (DR1), Disperse Red 19 (DR19), CANS, NSPP, CROCIN and liquid crystal. All these materials have relatively large first hyper polarisability β, so once being poled, the molecules can be aligned in a particular direction resulting in nonlinear EO effect in the polymer. These nonlinear dyes are introduced into the monomer before polymerisation. The structure is a guest-host system. The concentration of the dopant varies from about 0.05 %wt to about 5 %wt.

The key host material for the core and cladding of the fibre preform is a copolymer of methyl methacrylate (MMA) and ethyl methacrylate (EMA). The proportion of each of them is different in order to control the refractive index. The POF preform is fabricated using the "Teflon string inside cladding technique" developed by our research group [11]. Each preform has 2 fibre cores in parallel to each other, one of the core is doped and the other not doped. The outer diameter of the preform is 18mm, with the core diameter varies between 1 and 3 mm.

3. Poling technique

When the nonlinear dye material is doped into the polymer, the molecules have random alignment and therefore the doped polymer does not exhibit any macroscopic nonlinear effect. To pole the preform, we use an external high electrostatic field to align the dye molecules doped in the polymer matrix. The basic procedure is, when the temperature of the polymer is raised to a temperature near the glass transition temperature T_g, the dye molecules have enough mobility to rotate, so when the dipole moments of the dye molecules interacts with the applied electrostatic field, a partial alignment of the doped molecules is induced.

In our experiment, the conventional direct electric poling is adopted. The samples are 2 to 3 mm thick slices cut from the twin core POF preform. Two electrodes (flat surface metal pieces) connected to a high voltage source are placed across the preform slice. The preform slice and electrodes are put in an oil bath to allow temperature control. The transformer oil also helps to reduce the electric breakdown voltage since oil has better electric insulation than air. The voltage source is a DC supply which can go up to 50 kV. The current flow in the circuit is constantly monitored through a microammeter. A 30 kΩ resistor is placed in series in the circuit to avoid damage to the circuit during the electric breakdown on the sample.

Before the high voltage is applied, the oil bath is heated up to the required temperature which usually takes about 1.5 to 2.5 hours. Then while the temperature is maintained at this level, the voltage source is turned on, and the voltage across the sample preform slice is raised gradually to the maximum level. Both the high temperature and the high voltage are kept for a period of time to allow the realignment of the doping molecules. Then the temperature of the oil is lowered to the room temperature while the high voltage is maintained. This ensures that the alignment of the doping molecules is frozen in situ. Then the voltage source is turned off gradually.

4. Technique for EO effect measurement

In research work done on EO polymer, the EO nonlinear effect is usually measured using Mach-Zehnder interferometer scheme [8,12]. This method often suffers from system drifts because of the difference in the disturbing factors affecting the signal and reference paths. These factors such as temperature and light launching condition at end surfaces are difficult to control. The EO nonlinear effect measurement method we used is shown on Figure 1.

The light source is a 633 nm He-Ne laser source. A quarter wave plate is inserted to obtain circular polarization light. The circular polarised light is then passed through a polarizer with optical axis at 45°, so the light incident into the preform is polarised at 45°. The sample is placed on a micropositioner for fine 3D adjustment. A second quarter wave plate is placed at the output of the sample, being set at 45° optical axis too. Its purpose is to compensate for any intrinsic birefringence that comes from the sample itself. Then the output light is passed through an analyser, which is used to obtain $\pi/2$ phase bias. The output signal is detected by a photo amplifier, and measured by both a lock-in amplifier (for AC signal) and an oscilloscope (for DC signal). A RF functional generator is used to generate a sinusoidal wave at 3-4 kHz range, and this sine wave is then input into a transformer, which gives an output of about 550 V peak to peak signal. This signal is the modulation signal applied across the poled POF preform using 2 copper plate electrodes.

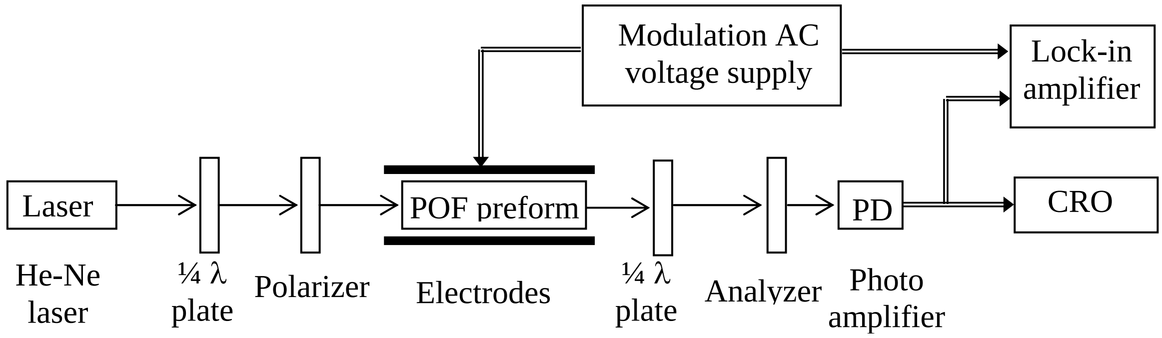


Figure 1: Set-up for EO Effect Measurement for the Poled POF Preform

For poled polymer which is doped with second order nonlinear materials, the model of Class *3m* crystal is used. Calculation shows that the nonlinear EO coefficient can be obtained by:

$$r_{33} = \frac{3\lambda d V_{AC}}{\pi V_{0RMS} L n_0^3 V_{DC}}$$

In the equation λ is the wavelength of the laser light, d is the distance between the 2 electrodes, L is the length of the sample, n_0 is the refractive index of the polymer material (similar for both ordinary axis and extraordinary axis), $V_{0\ RMS}$ is the RMS value of the input modulation AC signal, V_{AC} is the modulated signal obtained from the lock-in amplifier, and V_{DC} is the DC value of the output from the photo amplifier obtained from the oscilloscope.

The advantage of this method is that it is highly accurate because the common optical path of the two polarisation components essentially nullifies those disturbing factors affecting the phase measurement. It also takes into account the intrinsic birefringence of the sample and compensates it. Therefore this method can achieve high sensitivity, which means that it can detect second order EO nonlinearity as small as 1.0×10^{-15} m/V or even less. Also, this measurement system is very straightforward and simple, since no complicated signal processing electronics is required.

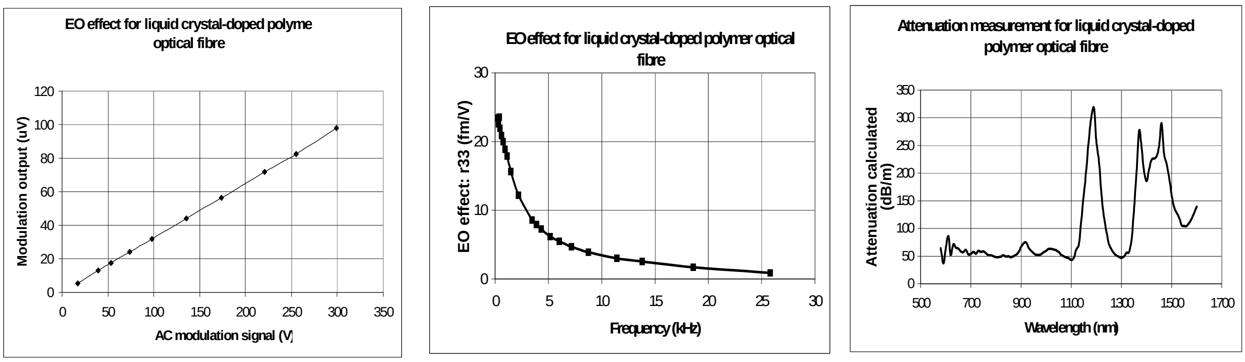
5. Experiment and result analysis

Using the poling and measurement techniques described above, various experiments were carried out to measure the electro-optic effect of some dye-doped polymer fibre preform samples. Experimental results show that, among different nonlinear dyes used, liquid crystal material gives the highest second order electro-optic effect.

Figure 2 (a) shows the second order EO nonlinearity induced as a result of poling a liquid crystal-doped polymer fibre preform slice with thickness of 2.7 mm. The poling was performed at 102.5°C at 35 kV for 4 hours (the 35 kV DC voltage was applied on the preform for another 1.5 hours during the process of lowering down the temperature). The horizontal axis is the RMS value of the applied AC modulation voltage, and the vertical axis is the signal detected by the lock-in amplifier. The result shows that the output modulated signal is linearly proportional to the applied modulation signal.

Figure 2 (b) is the frequency response of the electro-optic effect calculated. The result shows that the r_{33} is about 23.56 fm/V at modulation frequency of 400 Hz, and is about 7.30 fm/V at modulation frequency of 4.3 kHz. This result is greater than the EO effect result in doped polymer optical fibre reported by other research group [9], which is 2 fm/V. For NSPP doped polymer material, the r_{33} obtained is about 4.8 fm/V at 4.3 kHz.

Measurements were also carried out after the poled sample was heated up to near T_g, the result shows that the EO effect was no longer exist. And then the same sample was poled again and EO effect was obtained again at the similar value. From this it can be known that the nonlinear EO effect induced by poling is repeatable and reversible.



(a) (b) (c)

Figure 2. Electro-optic effect of poled liquid crystal-doped polymer optical fibre

Attenuation measurement is also carried out for the doped polymer material. Figure 2 (c) is the attenuation curve for the liquid crystal doped polymer material. The result shows that at frequency range below 1100 nm, the attenuation of the liquid crystal doped polymer optical fibre is about 50 dB per meter.

6. Applications and further improvement

Even though the electro-optic effect obtained from the current experiment is not as large as what was achieved in thin film structure, some applications can be suggested. One of them is a polymer optical fibre modulator, where the electrical modulation signal is applied on the twin core polymer fibre, only the doped core will produce electro-optic effect, the optical output, which is difference between the output at the doped and non-doped cores, is the modulated signal. Another application is polymer fibre voltage sensor, the variation of the optical output after the doped polymer fibre is proportional to the external electric field surrounding the fibre, therefore by measuring the fibre output, the external electric field can be calculated.

Further research work is being conducted to study how to increase the nonlinear effect, which includes improving the material preparation and poling procedure. It is believed that these improvement will lead to stronger electro-optic effect in doped polymer optical fibre, so that more applications can be achieved.

7. Conclusion

In this paper, simple techniques are described to induce and measure second order nonlinear EO effect in doped polymer optical fibre preform. Direct electric poling of the preform sample is used to introduce the second order nonlinearity and a simple yet accurate and sensitive transverse modulation scheme is used to measure of the EO coefficient. Comparing various nonlinear materials doped in the polymer fibre core shows that liquid crystal produces the highest electro-optic effect. It is expected that various EO devices based on polymer optical fibre (such as polymer optical fibre modulator and voltage sensor) could be constructed.

8. References

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