All-optical devices in polymer optical fiber

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Abstract

We report on polymer optical fiber devices for sensors, optical switches/ logic, and optical actuators. In this paper, we give a brief overview of polymer fibers, discuss recent all-optical switching results, and describe how an optical sensor and actuator can be built into a single fiber device. Future technologies that are made possible with such optical devices and photomechanical mechanisms are also discussed. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

In another article in this issue, we discuss how all electronic devices can be subdivided into the four classes: Data transmission and interconnects, sensors, computing/logic, and actuation devices [1]. In that article, an overview of the use of polymer fibers for interconnects and transmission was presented and several linear-optical characterization experimental results were reported. The first demonstration of electro-optic modulation in a polymer fiber with electrodes was also presented.

In this paper, we present all-optical switching results, and demonstrate how an optical fiber can be used as a smart actuator, in which an actuator and sensor are built into the same fiber. The results of this paper, together with the other article in this issue, show that all four device classes have been demonstrated in polymer fiber.

This paper is organized into two major sections. The first deals with optical logic and switching and the second deals with photomechanical effects, sensors, and actuators.

In the optical logic and switching section, we report on Sagnac experiments used to characterize the intensity-dependent refractive index of a single-mode dye-doped fiber. Subsequently, all-optical switching in a similar Sagnac interferometer is demonstrated. Finally, the first demonstration of non-linear switching between two parallel cores in a dual-core polymer fiber is reported.

The photomechanical-effect section describes the mechanisms that lead to a photomechanical response. Subsequently, actuator-based devices that use the photomechanical effect are described and data presented.

2. Optical logic and switching

In this section, we report on progress in optical switching studies in organic materials. We first dis-
cuss all-optical switching in bulk media followed by progress in switching studies in fibers.

2.1. All-optical switching

The Sagnac interferometer (sometimes called a loop mirror) has been shown to be a highly efficient geometry for optical switching because it is immune to external influences such as temperature variations and mechanical vibrations. Many examples of such switches made in silica-based fiber can be found in the literature [2–4]. It has also been used as a tool to measure the third-order susceptibility of a dye-doped waveguide [5]. In separate measurements, we have shown that the third-order susceptibility of dye-doped polymer optical fiber is, within an order of magnitude, comparable to liquid nitrobenzene [6]. We therefore begin by showing optical switching in bulk samples as a proof of principle.

The top portion of Fig. 1 shows a diagram of the all-optical switching experiment. A light pulse is launched into an asymmetric Sagnac interferometer. A small portion of the incident beam is removed from the Nd:YAG laser with a glass slide and monitored with a detector. The counterclockwise pulse goes through an attenuator before entering the sample so that the pulse intensity is too small to induce a phase shift due to the intensity-dependent refractive index. The clockwise pulse, however, experiences an intensity-dependent phase shift due to the sample. After this pulse leaves the sample, it also passes through the attenuator so that both pulses are the same intensity when they arrive back to the beam splitter — at which point they interfere. The amount of light reaching the output detector depends on the phase difference between the two pulses. For an interferometer with no sample, both pulses constructively interfere and all the light exits to the output detector. If the two pulses totally destructively interfere, all the intensity will go back to the laser source. Note that the weak pulse passes through the sample first. If the time ordering were reversed, the weak pulse would see the transient effects of the strong pulse. Indeed, this other arrangement could be used to measure the dynamical response of the sample. With the present set-up, only the instantaneous response within the 25 ps pulse duration is measured.

For a Kerr-material sample, the phase shift is linear in the incident intensity so the intensity at the output detector should be a sinusoidal function of the incident intensity. The bottom portion of Fig. 1 shows the ratio of the intensity measured by the output detector to the intensity measured by the input detector for a liquid nitrobenzene sample in a quartz cell. The theoretical curve is a sinusoidal function. Over an intensity range of about 300 MW/cm², the intensity dependent phase shift in the 2 cm long liquid cell is about π/2 radians. Given that polymer optical fibers have a comparable third-order susceptibility, a 20 cm fiber should yield a phase shift that corresponds to full switching. Below, we summarize results of single-mode fiber measurements and discuss how the state-of-the-art fiber materials fare against the nitrobenzene results.

2.2. Fiber Sagnac measurements

The Sagnac interferometer provides the ideal measurement scheme for single-mode fibers. Not
only is the technique sensitive enough to measure small nonlinearities, but it is also similar to the final device geometry. Fig. 2 shows a schematic view of the experiment.

The mode-locked pulse train from the laser source is passed through a rotating half-wave plate and polarizer to sinusoidally modulate the pulse train. The polarizer is set so that the electric field of the light is $45^\circ$ with respect to the table surface. A polarizing beam splitter separates the two polarizations. The ratio of intensities of the light passing through the polarizer is set to $1/r^2$ by adjusting the half-wave plate (not shown). The two counterpropagating waves travel through several components (described later) and are recombined at the beam splitter. The polarizer in front of the detector combines the two polarizations so that they can interfere. When the light intensity is low and the phase difference between the two beams is zero, constructive interference results and all of the light goes to the detector.

The inset shows the sinusoidal envelope of the input beam pulse train. Because the repetition rate of the laser is high (76 MHz) and the signal exiting the detector is integrated with a time constant that is long compared with the pulse spacing but short compared with the period of the sinusoidal envelope, we can view the laser source as continuous with a sinusoidal modulation in time. As in the all-optical switching experiment, an attenuator makes the interferometer asymmetric. Because the counterpropagating pulses are of orthogonal polarization, their rela-

Fig. 2. Sagnac–Kerr measurement of single-mode fibers.
tive phase can be adjusted by a pair of birefringent wedges (the compensator in the figure).

The experiment proceeds as follows. First, the amplitude of the detector output is measured with a lock-in amplifier that is synchronized to the frequency of the incoming sinusoidal modulation provided by the rotating half-wave plate. The phase shift is varied during this measurement to produce an interferogram. The amplitude of the interferogram is a measure of the input intensity in arbitrary units (usually measured in detector voltage). The top part of Fig. 3 shows typical data and a theoretical fit. The lock-in then measures signal at twice the modulation frequency as a function of the wedge position. The middle plot in Fig. 3 shows typical data and theory. The double peaked function is used to get both the

![Diagram](image)

Fig. 3. Interferogram at the modulation frequency, twice the modulation frequency, and the phase-theory (curve) and data (points).
real and imaginary parts of the third-order susceptibility. The bottom plot shows the measured phase and the theory for the phase. The important feature to note is that the peaks in the middle plot should approximately align with the maximum slope of the sinusoidal upper curve and the cusps in the middle curve should coincide with a 180° phase change. The data presented in all three curves are thus self-consistent.

The details of the data analysis are presented elsewhere [6]. Here, we tabulate some new results from this measurement technique on several single-mode fibers. Fig. 4 shows four dyes along with the phase shift measured for a 20 cm fiber with 10 μm core diameter and about 0.1 wt.% dye doping level. Note that the phase shift is expressed as a percentage of a π phase shift required for full switching. The peak power of the λ = 1.064 μm laser is 100 mW and for ISQ fiber yields a switching efficiency of 50% /W.

While these switching efficiencies are promising, there are other issues that need to be considered to evaluate squaraine dye-doped fibers for their usefulness in optical switching devices — such as two-photon absorption (TPA) and optical damage. If the material has a large two-photon absorption cross-section, the loss of light as a function of intensity due to TPA will be larger than the intensity change due to the phase shift. Mizrahi et al. defined a two-photon figure of merit [7], which is proportional to the ratio of the imaginary part of the third-order susceptibility to the real part. The constant of proportionality depends on the type of device. We have found that the HSQ dye, while not showing the largest switching efficiency, has the smallest figure of merit (< 1 in the worst case) and is therefore most appropriate for devices. We determined the imaginary part of the susceptibility using the analysis described in a previous paper [6]. Unfortunately, the uncertainty of this measurement is about 50%, so the imaginary values are not reported here.

The second issue is optical damage. We have found a very broad range of damage thresholds of fiber materials. It appears that the damage threshold depends on the processing history of the fiber, so it most likely depends on extrinsic properties such as materials purity and defects. For example, we have found optical damage in the range from 0.5 GW/cm² to 4 GW/cm². One fiber endured 4 GW/cm² for several weeks without any noticeable damage. This is in contrast to some fibers that damage at 0.5 GW/cm² after a couple laser shots. The best materials can thus tolerate the intensity levels that are required for all-optical switching.

2.3. Dual-core fiber switching

Our laboratories have succeeded in making dual-core single-mode fiber with nonlinear dyes [8], similar in geometry to dual-core glass fiber [9–11]. When the core separation is on the order of its diameter, energy flows back and forth between the cores as the light propagates down the fiber. Fig. 5 shows an end-view image of the dual-core fiber with λ = 1.064 μm light propagating down the guide. The bottom plot shows the intensity profile through the cores along the line drawn on the picture. The cores are made of 0.3 wt.% ISQ dye in PMMA and are separated by about one diameter. The coupling length — defined as the propagation distance over which all the energy transfers from one core to the other — of these fibers is measured to be about 9.4 mm.

Because the cores are nonlinear, the coupling length depends on the intensity of light launched into one of the fiber cores. The nonlinear coupling effect between waveguides was previously observed in silica fiber [12–14], and in a dual-core Er-doped fiber near-resonance [15]. We did a series of experiments in which the light exiting the fiber is imaged over a
range of input intensities. Each scan is digitized as shown above to determine the intensity of light that exits each core. Fig. 6 shows a plot of the normalized measured intensities exiting (i.e., light exiting each core divided by the total intensity that exits both cores) as a function of the incident intensity. For a linear waveguide, the result should be independent of the input intensity. Fig. 6 shows that 10% of the light couples from one core to the other over the range of incident powers. There are several difficulties that can explain why full switching was not observed. First, because the cores are close together, it is possible that when light is launched into one core, some of it couples into the second core. If, for example, 50% of the light were launched into both cores, no light transfer would be observed between cores because for any light transferring from core 1 to 2 there is an equal amount transferring from 2 to 1.

A more likely cause of incomplete energy transfer is the inhomogeneity of the fiber [8]. Because the length of the fiber used in these experiments is about 37 coupling lengths, random variations in the refractive index, spacing, and core diameter could lead to incoherent multiple scattering between cores, leading to about an equal amount of light in each core. This would lead to a decrease in the amount of light that transfers between cores. Assuming that Fig. 6 represents about 1 cycle, the approximate nonlinear refractive index is consistent with the phase shifts given in Fig. 4.

Polymer optical fibers thus appear to be a reasonable waveguide approach to making optical switching devices. Before high quality devices can be made, more work needs to be done in materials-processing studies and characterization.

For the geometry of our fiber (i.e., length, core size, core spacing, refractive index profile) and the incident peak power range, we would expect close to full switching, that is, all the light in one core should have coupled to the other core over the range of incident powers. There are several difficulties that can explain why full switching was not observed. First, because the cores are close together, it is possible that when light is launched into one core, some of it couples into the second core. If, for example, 50% of the light were launched into both cores, no light transfer would be observed between cores because for any light transferring from core 1 to 2 there is an equal amount transferring from 2 to 1.

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3. Optical sensors and photomechanical effects

A sensor is a device that converts one form of measurement to another. For example, a thermistor converts temperature to resistance — which can be measured by an electrical circuit. Optical analogs of such devices are finding applications due to their high sensitivity and immunity to electromagnetic pick-up. As an example, fiber Bragg gratings are being used as strain gauges in diverse environments that include bridges, spacecraft, and marine vessels [16]. The wavelength of light reflected from a Bragg grating depends on its period. When a fiber with a grating is stretched, the period changes and the reflected wavelength shifts. The fiber can therefore be simply interrogated with a broad spectral source. In general, structures that incorporate such sensors are often referred to as smart structures.

A photomechanical effect, on the other hand, is the optical version of a motor. For example, if the length of a material depends on the intensity of light illumination, it acts as an optical actuator — that is, light induces mechanical motion. In the following discussion, we give an overview of some recent work and speculate on applications that would be based on an optical actuator.

3.1. Origins of photomechanical effects

There are many mechanisms that lead to a photomechanical effect, including photothermal heating, electrostriction, molecular reorientation, and electronic excitation. The magnitude and speed of the response depends on material properties and sample geometry. Each response mechanism is briefly described below.

3.1.1. Photothermal response

When light energy is absorbed by a material and converted to heat, the material’s temperature increases, which, through thermal expansion results in a length change. While this mechanism is slow (millisecond time scale), the magnitude of the effect is large.

3.1.2. Electrostriction

It is well known that an electric field gradient, and hence a gradient in the intensity, results in a force on a dielectric material. In a single-mode polymer optical fiber, the light intensity is peaked at the center as shown in the other paper in this issue [1]. At the interface between the core and cladding, there is a large intensity gradient. The net result is an inward force on the core that acts to decrease the diameter and increase the length. Because fibers are thin, they maximize the intensity. Their long length, on the other hand, leverages small strains into a relatively large absolute length change. As an example, a \(10^{-4}\) strain in a 1 m long fiber yields a length change of 100 \(\mu\text{m}\). Such length changes are easily detectable with optical interferometric techniques. Furthermore, electrostriction should be fast (nanosecond response-time).

3.1.3. Molecular reorientation

When a beam of polarized light illuminates a molecule, its long axis will align along the electric field polarization of the light beam. If these molecules are imbedded in a polymer, the molecule–polymer interaction will stress the polymer and result in a deformation. This deformation can yield a shape change of the bulk material. Molecular reorientation in liquids and gasses is a well-known and well-studied process with sub-picosecond response [17]. Similarly, in solids, this mechanism is related to a reorientational phonon which is also fast [18] (resonances with picosecond periods) but the amount of deformation is small.

3.1.4. Electronic mechanism

The electron cloud of a molecule becomes distorted when it is placed in an electric field. The interaction potential between molecules in a bulk material depends on the electron clouds of the molecules. In the presence of a light beam, then, the spacing between molecules will be affected. While the electron-cloud deformation-time is ultrafast (femtosecond) it takes more time for the nuclei to move. The material response time would therefore depend on the structure of the solid.

3.2. Overview of photomechanical research

The first demonstration of a photomechanical effect in polymer fiber was based on the photothermal
mechanism [19,20]. In this work, a mirror is suspended from the end of a vertically-hanging photomechanical fiber in a vacuum chamber. The upper end is held in place by a collet. The mirror defines one arm of an interferometer. A fixed mirror outside the chamber defines the other arm. Because the position of the freely-hanging mirror is determined by the fiber length, the light intensity exiting the interferometer is a sinusoidal function of the fiber’s position. As such, the fiber length is related to the light intensity.

The light leaving the interferometer is fed back into the hanging fiber at the collet end as a source of optical feedback; that is, the length of the fiber depends on intensity exiting the interferometer; and the light intensity leaving the interferometer depends on the fiber length, and so on... This device was found to be multistable and acted as a vibration stabilizer. It could hold the length of a 30 cm fiber steady to within 3 nm — 1 part in 100,000,000. What is significant is that it combined all four device classes: The hanging mirror and interferometer acted as the sensor, the interference output intensity was encoded with the fiber length logic, the information was steered around the experiment with prisms in information transmission and the fiber acted as an actuator. This was therefore the first all-optical device demonstration in which no electronics are required.

This demonstration was followed by the design of a mesoscale version of the photomechanical stabilizer [21]. Fig. 7 shows a diagram of this device in a general characterization set-up. Because the dimensions of this device are in the micrometer to millimeter range, it is called a mesoscale photomechanical unit (MPU). The MPU is a short piece of fiber (from a few hundred micrometer in length up to 1 cm in length) with reflectors defined on each end. These reflectors can be made with a variety of methods including optical formation of Bragg gratings, end metallization, or making a retroreflector on each end.

The MPUs that we have evaluated operate as follows. The material is a dye-doped polymer, which through the photothermal mechanism, expands when illuminated by light. The end reflectors define a Fabry–Perot interferometer, so the MPU becomes 100% transmitting when the spacing between the mirrors is an integral multiple of the wavelength. Furthermore, the intensity inside the MPU is directly related to the transmitted intensity. Optical feedback is automatically built into the unit as follows. The intensity inside the MPU depends on the length and the length depends on the intensity. If, for example, the MPU is compressed, the light intensity inside increases, and, through the photomechanical effect, the length increases. The net result is that the MPU actively resists changes in its length.

Fig. 7 shows a general characterization experiment that uses two lasers, each of a different color. The control laser is launched into the MPU after two reflections from beamsplitters. Some of the light passes the first beam splitter (BS #1) and hits detector 3. Detector 3 thus monitors the control laser intensity. A second laser diode (called the probe

![Fig. 7. A mesoscale photomechanical unit in a general characterization experiment.](image-url)
The intensity transmitted through the MPU is monitored by diode 2. A filter at the output can be used to select one of the laser diode wavelengths. Part of the light reflected by the MPU is reflected by BS #2 and transmitted through BS #1 to detector 4, which can be used to monitor one or both beams (depending on filter choice).

In a typical characterization experiment, the control laser power is adjusted while both the probe intensity transmitted through and reflected from the MPU is monitored. The control laser thus changes the length of the MPU while the probe laser monitors the change. Alternatively, a speaker can be used to excite vibrations in the MPU so that the effect of the photomechanical response on mechanical impulse can be studied.

Fig. 8 shows the results of a single laser experiment [21]. The incident laser is ramped up and down and the transmitted versus the incident intensity is plotted. The observed hysteresis is predicted for a feedback system in which the phase of the light in the device depends on intensity. There are two possible sources of phase shift: an intensity-dependent length change and an intensity-dependent refractive index. Calculations show that both contribute.

Fig. 9 shows the results of a two-beam experiment, in which the transmitted probe intensity is measured as a function of time when the control laser is turned on and off. This is an example of all-optical modulation in which one beam can control the intensity of a second beam [22]. Here, the 1 cm long MPU is acting as a tunable interference filter where the control beam varies the spacing between the reflectors.

Fig. 10 shows an expanded view of the area in the dashed box in Fig. 9. The probe data is fit to a rising exponential from the time at which the pump pulse is turned off and a decaying exponential when the pump is turned on. The response time so determined is 100 ms. Our calculations show that the response time depends on MPU size and the thermal conductivity of the MPU and its surroundings. In principle (under ideal conditions), the response time can approach the microsecond range.

Applications of MPUs have already been reported. For example, an MPU was attached to a
Fig. 11. Two interacting MPUs can be used for complex sensing/processing.

``drumhead'' which is made of a mylar sheet that is stretched over the opening of a 1 cm diameter aperture [23]. When the MPU is powered with light, it actively suppresses vibrations in the drumhead.

3.3. Future applications

It is interesting to speculate on applications of polymer optical fiber. Given that polymers have been demonstrated to be capable of all four device classes, high performance hybrid devices that employ only optics may be envisioned. While even a single component feedback system has a complex response, when many such components are combined and allowed to interact, the result may be an ultra-smart system that is capable of performing complex reasoning.

Consider, for example, a system of two MPU units as shown in Fig. 11a. The one closer to the laser diode is transparent and is designed to have no photomechanical response — it acts as a passive sensor. The absorbing MPU, however, passes light depending on both the local stress and the intensity of light incident on the MPU. The MPU’s photomechanical response will therefore be determined from the stresses on each MPU. Furthermore, light reflected from the active MPU will interact with the transparent MPU, which in turn reflects the light back to the active MPU. This added interaction adds a degree of complexity that can be used to “program” the pair so that the response of the active MPU is a predetermined function of the geometrical arrangement of MPUs. This programming is achieved by picking the appropriate reflector spacing and distance between MPUs.

Fig. 11b shows a system that behaves similar to Fig. 11a except that the devices are wavelength...
addressable. That is, at one color MPU 1 is active and MPU 2 is passive while at another color, the roles are reversed.

Finally, we can imagine a string of MPUs as depicted in Fig. 12. In analogy to the dual MPU device, these associated networks of devices can be designed to be wavelength addressable and each device can be designed to interact with the full ensemble of all other devices in the chain. As such, each device would respond according to the stresses distributed along the chain of MPUs as well as the optical state of all the other MPUs. Polymer fibers could thus be used as the basic thread in making smart materials and smart structures.

The fabrication process for producing a string of MPUs is compatible with the fiber drawing process. One method for making a grating reflector is to cross two ultraviolet rays from outside the fiber as shown in Fig. 13. The period of the intensity grating depends on the crossing angle between the two beams, so a grating with a specified period — and therefore the spectral response of its reflectivity — can be burned into the fiber through cis-trans isomerization or physical surface relief grating formation [24]. A pulsed laser system could be used to burn gratings just before the take-up spool in the fiber-drawing apparatus, making it possible to fabricate many MPUs in long lengths of fiber.

The area of smart materials and smart structures using light as the power source is a new and unexplored area in which basic research is being applied to understanding photomechanical mechanisms for the purpose of determining structure–property relationships.

4. Conclusion

In conclusion, we have demonstrated that polymer optical fiber can be used to make all-optical switches, sensors and actuators. Furthermore, we have demonstrated an all-optical positioner and stabilizer that uses all four device classes, and have speculated on smart materials and structures. The set of devices described in this paper, and in our related paper in this issue on electro-optic fiber and transmission fiber [1] show that polymer fiber offers a palette of components that can be used to build devices that combine the four device classes.

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