 Spiro-oxazine photochromic fiber optical switch

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A photochromic all-optical switch in telecommunication-grade fiber is fabricated by filling a fiber Bragg grating Fabry-Pérot resonator with a spiro-oxazine solution. The narrow linewidth of the resonator allows for a high sensitivity of the resonance wavelengths to the index change. The switch is controlled by low intensity UV light exposure, and operation at infrared telecommunication wavelengths is demonstrated. The switching speed on the order of minutes has been achieved.

All-optical photonic switches, which use light to control and gate the propagation of optical pulses, can have a significant impact on molecular photonics, optical computing, and networking. For current all-optical switching technologies, the major hurdles that limit their widespread application are low device responsivities and high optical intensities required to achieve the switching. In this letter, we report an all-optical switch that combines a “smart” fiber-based photonic structure with photochromic materials, and demonstrate nearly complete on-off switching under low intensity UV light exposure.

Photochromic compounds (including spiroheterocyclic compounds such as spiropyrans and spiro-oxazines) have a reversible response to light exposure and are ideal for optical switching applications. For example, spiro-oxazines have recently attracted much attention due to the high yield cleavage of spiro-C–O bond under ultraviolet (UV) exposure and the nearly total recovery of the back reaction after UV exposure. A photochromic optical switch can be based on either the conformational changes or the absorption changes of the chromophores. For spiro-oxazines, the colorless closed form [I, Fig. 1(a)] dominates the ground state equilibrium state while deep blue colored open form (II) is preferred under UV exposure, causing a drastic increase in absorption around 600 nm. However, for most telecommunication applications, the working wavelengths (e.g., around 1500 nm) are far away from the absorption band of the photochromic materials. Hence, a photochromic switch at these wavelengths must exploit changes in other optical properties, besides absorption, resulting from the photochromic reaction. For the fiber-based all-optical switch reported here, we adopt the most direct approach, which is to utilize the refractive index changes induced by the changes in the electronic delocalization in the chromophore.

5-chloro-1,3-dihydro-1,3,3-trimethylspiro-[2H-indole-2,3′-(3H)phenanth[9,10-b][1,4]oxazine] (SPO), whose structure is shown in Fig. 1, is chosen as the working material for the switch. Under UV exposure, the ring open reaction produces the merocyanine form II. The charge transfer transition of this merocyanine chromophore changes the material absorptivity around 600 nm and consequently modifies the refractive index in the infrared (IR) wavelengths. After the UV exposure, the merocyanine structure returns to the spiroconformation (I) and the material refractive index returns to the original value.

To utilize this photoinduced index change to control light propagation, we put this reaction in a Fabry-Pérot (FP) microresonator. An optical resonator is highly sensitive to

FIG. 1. (Color online) (a) Molecular structures of the closed state (I) and the open state (II) of the SPO chromophore. (b) The schematic of the fiber optical switch device. (c) The two fibers are separated by a gap of length D. The gratings are separated by a length L. (d) An optical microscope photograph of the photochromic fiber switch device. The diameter of the fiber is 125 µm and the gap distance D is 40 µm.

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changes in the refractive index of the cavity because an index change alters the intracavity optical path length, thus modifying the resonance condition of the cavity. Using this principle, FP resonators have recently been used in fiber for sensing applications.\textsuperscript{15–17}

A drawback to using SPO is that the photochromic reaction is slow in polymer blends and is prohibited in crystal form\textsuperscript{18} as the conformation change is impeded by the solid phase. Therefore, we combine the SPO liquid solution with optical fibers. Two 2.5 mm long Bragg gratings with reflection bands around 1520 nm and reflectivity ~95% are written in the core of an SMF-28 single-mode fiber by a KrF laser (248 nm) using quartz phase mask. The two Bragg gratings serve as the end mirrors of the FP cavity. The fiber was cleaved in the middle of the two grating reflectors, and the two halves are fixed in a glass tube with a gap of length $D$ in between them [Fig. 1(c)]. The separation of the two gratings is $L$. In our device, $D=40$ $\mu$m and $L=1.4$ mm. An opening is cut at the top of the glass tube so that the SPO solution can be deposited into the air gap [Figs. 1(b)–1(d)]. To avoid reflection at the interface between the fiber ends and the solution, we use fused silica index matching fluid as the solvent for the SPO powder. The concentration of the solution is $4\times10^{-3}$ mol dm$^{-3}$.

The fiber and the solution in the gap contribute to the total optical length of the FP cavity. Under UV exposure, the refractive index of the SPO solution increases and therefore extends the optical length of the FP cavity. The transmission and reflection spectra of the device are shown in Fig. 2. The transmission spectrum shows a stop band centered at 1520.06 nm with bandwidth ~0.5 nm. The reflection spectrum is complementary to the transmission spectrum. From Fig. 2, the loaded quality ($Q$) factor of the device, which is indicative of the total resonator loss, is $4.5\times10^4$, and the free spectral range (FSR) of the FP resonator is 0.23 nm.

The resonance wavelengths are redshifted when the photochromic solution is exposed by 365 nm UV light with an intensity of 10 mW/cm$^2$ in ambient conditions. Theoretical fitting of the spectrum under UV exposure shows that the 0.06 nm redshift of the resonance wavelength corresponds to a refractive index increase of $4.0\times10^{-3}$ in the photochromic solution. Thus, the responsivity of the optical switch $\Delta\lambda/\Delta n$ is 15 nm. For this high-$Q$ resonator device, the resonance peaks are narrow (linewidth of 0.034 nm) such that a 0.06 nm shift is sufficient to move the resonance wavelengths over the width of the peaks. Therefore, the resonance wavelengths without UV exposure can become completely off-resonance during the UV exposure.

Figure 3 is the time-dependent transmission and reflection spectra of the photochromic switch during and after the UV exposure. The spectra around the resonance peak/notch are plotted as color map diagrams. The warmer color indicates a higher intensity while the colder a lower intensity, as shown in the color bar. The center of the resonance peaks/notches is plotted as circles. The UV exposure period and the recovery are also labeled.
The switching speeds are limited by the photochromic reaction rate of SPO in nonpolar solvents. However, this response time is commensurate with related reports and can be optimized by the molecular engineering of the photochromic materials.\textsuperscript{20}

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\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig4.png}
\caption{(Color online) Modulation of the IR signal light at 1520.06 nm due to the photochromism induced by the UV exposure.}
\end{figure}

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