All-fiber bidirectional optical modulator derivates from the microfiber coated with ITO electrode

PINGPING TENG, [1] **MENG LUO,**[1] **XINGHUA YANG,**[1,*] **DANHENG GAO,**[1] **NIGEL COPNER,**[2] **ZHIHAI LIU,**[1,*] **JUN YANG,**[1] **SHUAI GAO,**[1] **KANG LI,**[2] **MARK BOWKETT,**[2] **LIBO YUAN,**[1,3]

[1]*Key Lab of In-Fiber Integrated Optics, College of Science, Harbin Engineering University, Harbin 150001, China*
[2]*Wireless & Optoelectronics Research & Innovation Centre, Faculty of Computing, Engineering & Science, University of South Wales, Wales, CF37 1DL, UK*
[3]*Photonics Research Center, Guilin University of Electronics Technology, Guilin 541004, China*
**Corresponding author: yangxh@hrbeu.edu.cn; liuzhihai@hrbeu.edu.cn*

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A cheap, compact, and simply prepared all-fiber bidirectional optical modulator based on the Pockels effect of water and the band population effect was first proposed and demonstrated. The transparent conductive oxide indium-tin-oxide (ITO) was coated on the surface of a non-adiabatic microfiber and first used as a modulating electrode on the microfiber. The device was realized by just submerging the microfiber in water. With supplying an electric field perpendicular to the interface between the microfiber and water, the refractive index (RI) was modulated in the electric double layer (EDL) near the tapered region of the microfiber, under the Pockels effect of water. Subsequently, the interference spectrum was modulated. Meanwhile, the intensity of the light was modulated due to the band population effect in the space-charge layer (SCL). In this letter, the proposed all-fiber optical modulator can realize simultaneous bidirectional modulation of the phase and intensity of output light. Experimentally, the maximum phase shift and the extinction ratio were 4.38 nm and 4.87 dB at 1550 nm, respectively. Significantly, the work used the Pockels effect of water and the band population effect to realize an all-fiber optical modulator, shows great potential in the optical phase modulators, optical switches, and electric field sensors.

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The Pockels effect was considered as the only present in the crystal without inversion symmetry [1,2]. However, with the continuous deepening research of electrochemical, the research on the interface of the electrode and the electrolyte has made great progress. An EDL and a SCL were reported between the interface of the electrode and water [3]. In EDL, the electrical properties of the electrode surface can induce the orientation of the oxygen atoms of the water molecules which causes orientational order of the water molecules. Under the effect of an external electric field, the spatial distribution of water molecules in the EDL change, causing the effective RI of the water to change. Researchers have experimentally proved that the RI of water changes in the EDL [4]. The electronic response of water is called the Pockels effect of water which was represented by the coefficient n_1 in the electric-field dependent RI $n=n_0+n_1E+n_2E_2+\cdots$. The giant Pockels effect of water in the EDL has been measured [5]. Therefore, the Pockels effect of water in EDL shows great potential for the preparation of a micro-nano-sized optical modulator.

Optical modulators as one of the essential devices in the optical system are widely utilized in various optical systems, such as the optical interconnect and environment monitoring systems. Up to now, a great of schemes for realizing optical modulator has been developed. Among the numerous optical modulators' schemes, optical modulators grounded on optical fiber have drawn great attention from the research. Different from those modulators grounded on planar waveguides [6-8], all-fiber optical modulators have many essential advantages. On the one hand, all-fiber optical modulators can be conveniently integrated with current optical systems, such as wavelength division multiplexing (WDM) system and fiber laser system, with low insertion loss. On the other hand, for utilizing the all-fiber structure interferometer such as Mach-Zehnder interferometer system [9], Sagnac interferometer [10], and Fabry-Perot interferometer [11], a phase modulator can be easily realized. Most of the schemes for all-fiber optical modulators are implemented by using expensive two-dimensional materials such as graphene, black phosphorus (BP), and MXene to modify optical fiber. Therefore, it is essential to propose a simple and inexpensive all-fiber modulator.

In this letter, a cheap, compact, and simply prepared all-fiber optical modulator was proposed. The device was realized by using the ITO as an electrode coated on the upper surface of a non-adiabatic microfiber, which was simply submerged in water. By applying an electric field between the interface of the microfiber and water, the RI of the water in EDL was changed under the Pockels effect of water. The RI change in EDL causing the phase shift of the interference spectrum emitted from the microfiber. By changing the direction of the applied voltage, bidirectional modulation of the phase can be achieved. Meanwhile, due to the band population effect in SCL, the optical modulator also realized the modulation of light intensity, simultaneously. The maximum phase shift and the extinction ratio were 4.38 nm and 4.87 dB at 1550 nm, respectively. In terms of response time, the optical modulator has a rising time of 2.2 s and a falling time of 2.3 s.

The experiment setup is shown in Fig. 1. The non-adiabatic microfiber was obtained by the flame pulling method, which has been described in our previous work [12]. The ITO film was deposited on the upper surface of the microfiber as a surface electrode with a length of 5 cm by radio frequency (RF) sputtering, using a commercial magnetron sputtering deposition system (JGP-450B). The inset of Fig. 1 shows the scanning electron microscope (SEM) of the microfiber coated with ITO. The thickness of the ITO film obtained by RF sputtering was approximately 35 nm which was measure by 3D surface profiler (zygo) as shown in Fig. 2. And the resistance of the ITO film was $5.1*10^3$ Ω. The loss caused by sputtering ITO was less than 0.3 dB. The microfiber deposited with the ITO film was fixed in a PMMA groove. A conducting wire was connected to the surface of the ITO electrode with silver paste. Then 50 μL deionized water was injected into the PMMA groove to submerge the microfiber. Another electrode was placed 1 mm away from the microfiber in the water of the PMMA groove. The insertion loss of the device was 7.6 dB at 1550 nm. A signal generator (SG) was connected to the transparent electrode ITO and water, respectively. The signal light emitted by the amplified spontaneous emission (ASE) light source (1520-1610 nm) was guided into the microfiber, and an optical spectrum analyzer (OSA, AQ-6317B) was applied to monitor and record the interference spectrum.

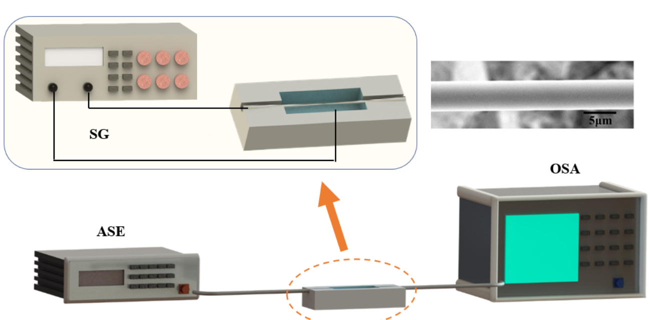

Fig. 1 The setup of the proposed optical modulator based on the Pockels effect of water and the band population effect. (The inset: the SEM of the microfiber coated with ITO film)

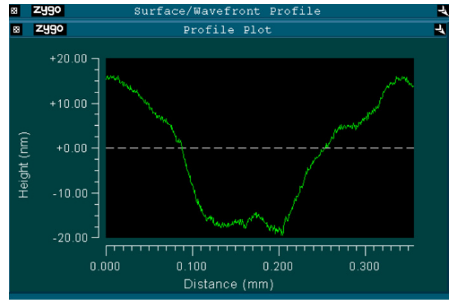

Fig. 2 The thickness of the ITO film sputtered on the upper surface of the microfiber.

In the experiment, we assume that the direction of current from ITO to deionized water is positive. The interference spectrums were monitored and recorded by supplying different powers of positive voltage ranging from 0 to 1.3 V. The results are shown in Fig. 3. The original spectrum with a contrast ratio of 3.41 dB and free spectral range (FSR) of 10.94 nm. As increasing the voltage of applying to the device, the interference spectrum was modulated to the long-wavelength direction. In the experiment, the maximum amount of the spectral shift was 4.38 nm and the contrast ratio of the interference spectrum also increased to 4.53 dB with the application of a 1.3 V positive voltage. For the proposed optical modulator, at the interface of the transparent electrode ITO and the deionized water, an EDL and a SCL were formed as shown in the schematic diagram of Fig. 4. The energy dispersive X-ray spectroscopy (EDS) shows the ITO was coated on the microfiber in Fig. 4. With supplying a positive voltage, the molecular arrangement of interfacial water in EDL was modulated, which lead to the RI of water changes. The change of effective RI caused the cladding mode of the microfiber to change, which leads to the phase shift of the interference spectrum. For the contribution of the change in RI, the contribution of the RI in the EDL is much greater than the RI change of ITO in the SCL [13,14]. Therefore, in the experiment, the contribution to the spectrum shift for the optical modulator mainly comes from the Pockels effect of water. We attribute the increase of the contrast ratio to the band population effect in SCL.

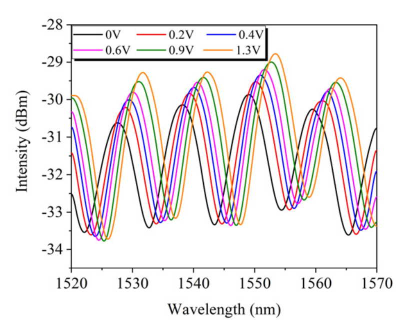

Fig. 3 The spectral shift of the proposed device with the different positive voltage.

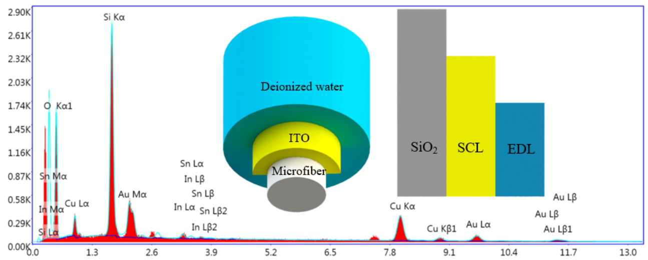

Fig. 4 The schematic diagram of the modulator and the EDS of the microfiber coated with ITO film.

The dependence of the positive voltage intensity and the phase shift was fitted and shown in Fig. 5. It should be noticed that the fitted curve doesn't show a linear relationship. However, according to the Pockels effect (linear electro-optic effect), the intensities of voltage and the spectrum shifts should present a linear relationship. To the best of our knowledge, the reasons for this phenomenon may be multiple. On the one hand, the electrons transfer between the deionized water and the ITO caused non-linear changes. Although the experimental conditions have been strictly limited, deionized water will still be doped with gas causing the water to present some characteristics as a conductor. When a voltage is applied to the interface between water and the ITO electrode, the electrons will transfer at the interface between the ITO film and deionized water. On the other hand, the asymmetrical distribution of the ITO film on the surrounding surface of the microfiber and the surface roughness of the ITO films cause the RI change in the EDL to occur only on the upper surface of the microfiber. Therefore, the RI change of cross-section of the microfiber presents a nonlinear change. Under the combined action of two elements, the amount of phase shift presents non-linear change. By controlling the gas content in the deionized water, and uniformly coating the ITO electrode on the surface of the microfiber, the remaining factors to the proposed optical modulator can be eliminated, enabling the linear control of the spectrum shift by changing the voltage intensity.

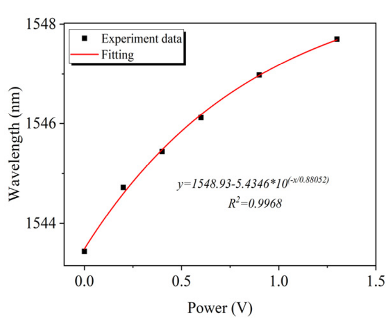

Fig. 5 The dependence of the wavelength shift with the application of positive voltage.

To further investigate the performance of the optical modulator, a series of negative voltage was supplied to the device. As shown in Fig. 6, the spectrum was modulated to the short-wavelength, and the contrast ratio of the interference spectrum was decreased. The direction of the spectrum shift was opposite to the direction of wavelength shift with the application of positive voltage, which proves that the phase shift was not caused by the thermal effect. The dependence of the negative voltage intensity and the phase shift also character a non-linear relationship as shown in Fig. 7. And the light intensity showed a significant drop, correspondingly. The maximum extinction ratio was 4.87 dB at 1550 nm. The reason for this phenomenon is that the accumulation of electrons in the SCL induces an increase in the absorption of near-infrared light by ITO [13]. When the direction of the applied voltage changes, the orientation of the water molecules changes, resulting in the RI change to the opposite change. It can be seen that by applying the same amount of positive and negative voltage, the phase shift was different. We attribute it to the different orientations of the water molecules at different direction voltage in the EDL. When the applied electrode charge changed from a positive charge to a negative charge, the average molecular direction of the interface water molecules changes from oxygen-down to oxygen-up [15]. Meanwhile, to investigate whether the spectrum shift was related to the ions in the solution, 0.1 M NaCl and 0.1 M KCl solution replaced the deionized water were added to the PMMA groove, respectively. The obtained phase shifts were consistent with deionized water.

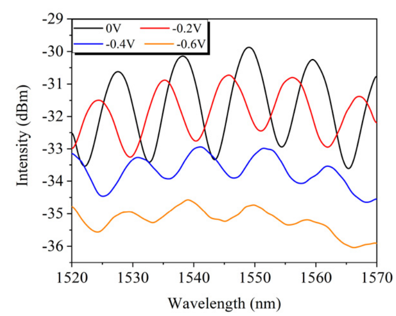

Fig. 6 The spectral shift of the proposed device as the negative voltage.

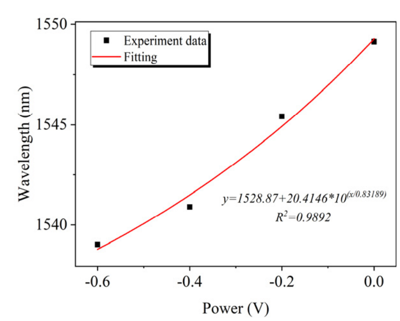

Fig. 7 The dependence of the wavelength shift with the application of negative voltage.

The dynamic response of the optical modulator was also investigated. The ASE source was guided into the microfiber, and the output of the signal propagated through a monochrome which was connected to an InGaAs detector. With the applied voltage of -0.2 V, the intensity of 1550 nm was monitored and recorded as shown in Fig. 8. When the power is switching on and off periodically, the dynamic response curve shows good stability. In terms of the responds time of the device, the rising and falling time were 2.2 s and 2.3 s as shown in Fig. 9. For the proposed optical modulator, the rising edge and the falling edge of the response time may cause by the re-arrangement time of water molecules surrounding the microfiber. However, the rising and falling time are much large than the orientational response of water in EDL. We attribute it to the excessive water around the microfiber and the asymmetrical coated ITO film. To further optimize the device, it is expected to reduce the time of rising and falling edges by applying more sophisticated processing techniques to reduce the volume of the water and the improvements to the sputtering device.

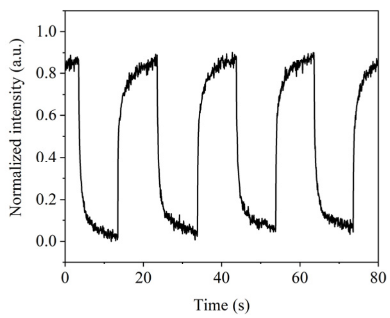

Fig. 8 The dynamic response of the device when the power is periodically switched on and off.

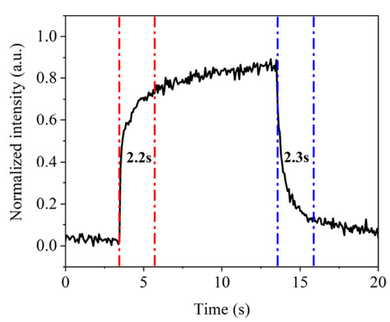

Fig. 9 The response time of the device with the power periodically switching on and off.

In conclusion, a cheap, compact, and simply prepared all-fiber bidirectional optical modulator based on the Pockels effect of water and the band population effect was proposed. The ITO was coated on the surface of the tapered optical fiber and first used as a modulating electrode on the tapered optical fiber. At the interface of water and the ITO electrode, due to the Pockels effect of the water, the re-arrangement of water molecules in space caused the RI around the microfiber to change. Subsequently, the phase of the interference spectrum was modulated. By changing the direction of the applied voltage, bidirectional modulation of the phase can be achieved. Meanwhile, due to the band population in SCL, the intensity was modulated. In this letter, the proposed optical modulator can realize simultaneous bidirectional modulation of the phase and intensity modulation of propagated light in the microfiber. Experimentally, the maximum spectrum shift and the extinction ratio were 4.38 nm and 4.87 dB at 1550 nm, respectively. Significantly, by integrating ITO as an electrode on the surface of the microfiber to achieve a bidirectional optical modulator, the work shows great potential in optical phase modulators, optical switches, and electric field sensors.

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Disclosures. The authors declare no conflicts of interest.

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