All fiber electro-optic modulation using a Sagnac fiber-loop with an internal twin-electrode fiber

Bok Hyeon Kim, Songbae Moon, Un-Chul Paek, and Won-Taek Han
Department of Information and Communications, Gwangju Institute of Science and Technology (GIST)
1 Oryong-dong Buk-gu, Gwangju 500-712, Republic of Korea, wthan@gist.ac.kr

Abstract: All fiber electro-optic modulation using an internal twin-electrode fiber in a Sagnac fiber-loop was demonstrated. The modulation was explained by the electrically induced birefringence due to the electro-optic Kerr effect in the fiber.

1. Introduction
Since the attractive observation of the strong second harmonic generation in an optical fiber [1], much scientific and technical effort has been made to enhance the electro-optic characteristics of the fibers because of their high potential in all-fiber applications such as optical modulation, switching, wavelength conversion, and tunable filtering in optical communication and sensing systems [2, 3]. Recently, using fibers with internal single or twin-electrode made by the electrode formation technique using molten alloy [4], a polarization controller based on the stress induced birefringence and an active mode-locked laser constructed by an all fiber electro-optic modulator were demonstrated [5, 6].

Since the Sagnac fiber-loop (SFL) interferometer has advantages such as the insensitivity to the input polarization and the surrounding temperature, the large extinction ratio, and the wavelength tenability, it has been used as the wavelength division multiplexing filters and the fiber laser ring cavities [7, 8].

In this study, we report an all fiber electro-optic modulation device using a SFL based on an internal twin-electrode fiber. The internal twin-electrode fiber used in the SFL was made by injecting a molten Pb-Sn alloy into the two holes of a fiber. The operating mechanism and the characteristics of the modulation induced by the electric field in the SFL interferometer were investigated.

2. Experiment
An optical fiber preform with germanium doped core and silica cladding was made by the modified chemical vapor deposition (MCVD) process and two holes with diameter of 4 mm were drilled at both sides of the core. Then the preform was drawn into an optical fiber with diameter of 125 µm preserving the holes. The diameters of the fiber core and the holes were 6.1 and 20.1 µm, respectively, and refractive index difference between the core and cladding was 0.0046.

The molten alloy infiltration technique was used for the formation of electrodes in the fiber [4]. A molten alloy with the composition of 63%Sn-37%Pb was injected into the holes of the fiber by the aid of nitrogen gas with the pressure of 10 bar. As a result, an optical fiber with a continuous internal twin-electrode with the length of 1.49 m was obtained. Figure 1 shows the cross section of the optical fiber before and after the infiltration of the electrodes. The distance between the center of the core and the nearest surface of the electrodes and the edge to edge distance between the electrodes were 14.6 and 39.7 µm, respectively. For electric contact with the electrodes of the fiber, the side of the fiber was polished using an abrasive pad and the electrodes were connected with metal wires using a conducting silver epoxy.

Fig. 1. Cross-section of the optical fiber (a) before and (b) after the formation of the internal twin-electrode.

Schematic of an all fiber electro-optic modulator using a SFL based on the internal twin-electrode fiber was shown in Fig. 2.

As shown in the figure, the 1.49 m twin-electrode fiber was connected inside the SFL by fusion splicing and a fused optical fiber coupler with the coupling ratio of 3 dB was used for the loop. CW light at 1550 nm with the optical power of 2.5 mW from a tunable laser source (TLS) was injected into the input port. Then the optical signal from the output port was measured by a photo-receiver after applying the sinusoidal AC electric voltage with the peak-to-peak intensity of 280 V at the modulation frequency of 5 ~ 40 kHz that superimposed on the different biased DC voltage in the range of 0 ~ 8 kV. To maximize the intensity of the optical signal by changing the state of the polarization, a polarization controller was used inside the SFL.

Fig. 2. Schematic setup of the electro-optic modulation device using the SFL based on the internal twin-electrode fiber.
4. Results

Figure 3 shows the modulated optical signal measured by applying AC signal with the peak-to-peak voltage of 280 V at 10, 20, and 40 kHz on the biased DC voltage of 7 kV. It was found that the shape and the frequency of the optical modulation were in accordance with those of the applied electric signal. The peak-to-peak intensity of the modulation was also found to be almost constant over the modulation frequency from 5 to 40 kHz. As shown in the figure, the modulation intensity at 10, 20, and 40 kHz was about 55% of the maximum of the optical signal regardless of the modulation frequency.

![Fig. 3. Modulated optical signal of the SFL applied with the peak-to-peak AC voltage of 280 V at 10, 20, and 40 kHz on the biased DC voltage of 7 kV.](image)

Figure 4 shows the peak-to-peak intensity of the optical signal with the applied DC voltage from 0 to 8 kV. For the optical modulation, the small AC voltage with the constant peak-to-peak intensity of 280 V at 20 kHz was applied to the fiber after being superimposed on the different DC voltages.

![Fig. 4. Peak-to-peak intensity of the optical signal modulated by the AC electric signal of 280 V at 20 kHz with the different biased DC voltages.](image)

As shown in the figure, the peak-to-peak intensity of the optical signal modulated at the DC voltage of 0 kV was almost zero, while the peak-to-peak intensity strongly increased with the increase of the DC voltage up to 7 kV.

When the DC voltage reached at 8 kV, the intensity slightly decreased.

The operating mechanism of the electro-optic modulation in the SFL is explained by the electric field induced birefringence. Even though the second order optical nonlinearity is originally not permitted in glass because of its isotropic structural characteristics, the effective second order nonlinearity, \( \chi^{(2)}_{\text{eff}} \), can be induced by the externally applied electric field, \( E \), and the third order nonlinearity, \( \chi^{(3)} \), of the glass [9]

\[
\chi^{(2)}_{\text{eff}} = 3\chi^{(3)}E/2.
\]  
(1)

It is also known that the induced second nonlinearity by the external electric field serves the polarization dependence according to the direction of the applied electric field [10, 11].

\[
\chi^{(2)}_{\text{eff}} \rmp \chi^{(2)}_{\text{eff}} \rt = \gamma \neq 1
\]  
(2)

where the notations of TM and TE mean the parallel and perpendicular to the direction of the applied electric field, respectively.

When the electric field is applied to the fiber, the birefringence is induced by the equation (2) and the electro-optic Kerr effect, \( \Delta n(E) = \chi^{(3)}E/n_0 \), where \( \Delta n \) the refractive index change by the electric field and \( n_0 \) the refractive index of glass.

Therefore the internal twin-electrode fiber acts as a wave retarder and it affects the polarization state of the light inside the SFL. As a result, the optical modulation is induced by the temporal change of the polarization state due to the applied electric field in the SFL.

5. Conclusion

All fiber electro-optic modulation using the nonlinear Sagnac fiber-loop mirror based on an internal twin-electrode fiber was demonstrated. The obtained 20 kHz modulation was explained to be due to the birefringence induced by the electro-optic Kerr effect of the fiber.

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