Mid-infrared optical modulator based on D-shaped PCF

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Abstract— **Recently, photonic crystal fibers (PCFs) have become of compelling interest due to their diverse applications, especially in the mid-infrared (mid-IR) wavelength regime. In this work, an optical mid-IR modulator based on D-shaped PCF with germanium-antimony-tellurium (GST) as a phase-changing material (PCM) is presented and analyzed. Because of the phase transition of the GST material between amorphous (dielectric-like) and crystalline (metal-like) states, the modulation process can be attained. The optical losses of the fundamental TE mode supported by the PCF core in amorphous (ON) and crystalline (OFF) states are investigated. The results reveal that the suggested modulator has an ultra-high extinction ratio (ER) that approaches 206 dB, while the insertion loss (IL) is less than 9.8×10^{-6} dB throughout the studied wavelength range of 3 – 5.8 µm with a device length (L_D) of 0.5 mm.**

***Index Terms*— Photonic crystal fibers, Phase changing materials, GST, Optical modulator.**

Optical modulators[1–3] are major components in optical communication systems because of their efficiency in manipulating the light passing through the device. Optical modulators with enormous data capacity, low loss transmission, and external electromagnetic interference immunity have great significance in modern photonic integrated circuits (PICs). Recently, photonic crystal fiber (PCF)-based structures have been utilized to design efficient optical modulators[1] due to its numerous advantages including the unprecedented light control mechanisms. Further, PCFs have been widely used in different photonic applications including biomedical sensors[5,6] and polarization rotators[7,8].

Mid-infrared (mid-IR) wavelength regime plays an important role in both research and industry[9]. In this context, silicon (Si) has gained a growing interest in optical communication systems because it has low optical loss in mid-IR[10], which encourages the migration of photonic circuits based on Si to this wavelength range. Furthermore, carrier control in silicon gives different effective applications, such as optical modulators[11].

Phase change materials (PCMs) are new adaptive materials with unique characteristics. The state of PCMs can be switched by applying an external electric field or changing the temperature[12]. Thus, PCMs have a growing interest due to their switching speed, low energy consumption, and scalability[13].. One of the well-known PCMs is germanium-antimony-tellurium (GST). The GST material has two phases: the amorphous phase with very low absorption of light, and the crystalline phase that shows a very high optical attenuation.

An optical modulator based on silicon D-shaped PCF with GST material (GST-D-PCF) is proposed and analyzed. The presented GST-D-PCF modulator has a thin layer of GST to modulate the input signal. When the GST is in its amorphous phase, the modulator will be in its ON state with a very low IL. By changing the phase of the GST material into the crystalline phase, the OFF state is induced with high optical loss. The full vectorial finite element method (FVFEM)[14] is utilized to calculate the modal dispersion parameters: effective index (n_{eff}) and loss of the supported modes through the reported PCF structure. Moreover, the 3D finite difference time domain (3D-FDTD) method[15] is employed to investigate the propagation of light through the proposed structure.

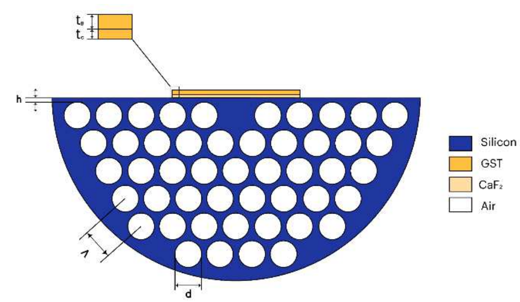

Fig. 1. Cross section of the proposed GST-D-PCF.

Figure 1 depicts the 2D cross-sectional view of the designed GST-D-PCF optical modulator. The proposed D-PCF has 5 rings of air holes arranged hexagonally in Si background material. The GST layer is deposited directly above a thin spacer of calcium fluoride (Caf$_2$) material. The CaF_2 material can be used as a thin spacer to allow high index contrast with high transmission in the Mid-IR range. The GST layer is close to the core region to facilitate the interaction with the input light, thus, improving the modulation process. The refractive index of the GST material in both amorphous and crystalline phases is taken from[16]. The material dispersion of the Si and CaF_2 materials in the mid-IR regime can be calculated through the well-known Sellmeier equation[17,18]. The Lumerical software package[19] is used to investigate the propagation properties of the guided TE and TM modes through the GST-

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D-PCF core. The reported modulator has an initial device length of 50 µm where an optimization study can be made to reduce the device length with good extinction ratio (ER) and large bandwidth. Figure 2 displays the field evolution through the propagation direction of the reported structure. As may be seen in Figs. 2(a) and 2(b), the TM core mode has a very low optical loss through the propagating length for both the amorphous and crystalline phases of GST. However, the TE core mode is strongly absorbed by the GST material in the crystalline GST phase as illustrated in Fig. 2(c). Furthermore, Figs. 2(b) and (d) indicate that the amorphous GST phase causes very small propagation losses to both TE and TM modes, respectively. Therefore, the modulation behavior is obtained efficiently through the TE mode.

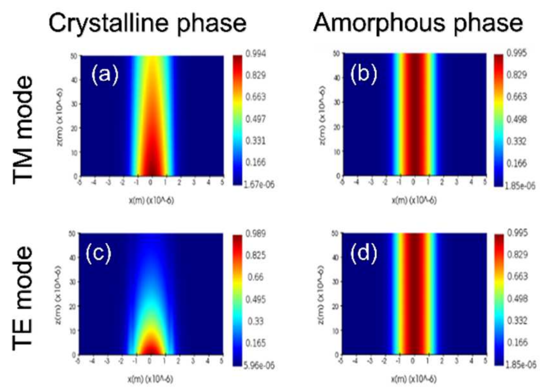

Fig. 2 Light propagation of TM mode for (a) crystalline phase, (b) amorphous phase, and TE mode for (c) crystalline phase, and (d) amorphous phase.

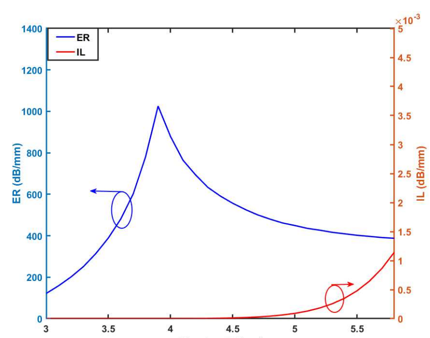

Fig. 3 Wavelength-dependent ER and IL of the TE core mode.

Generally, the performance indicators of the optical modulators, ER and insertion loss (IL), are used to measure the characteristics of the suggested GST modulator. The ER can be defined as the optical loss difference between OFF (crystalline phase) and ON (amorphous phase) states and it should be maximized. Additionally, the IL is the optical loss of the ON state (amorphous phase) and it should be minimized. The main target in this work is to achieve low IL and ultrahigh ER with compact device length. Figure 3 depicts the wavelength-dependent IL and ER for the TE core mode of the proposed structure. It may be seen that the IL is very low through the studied wavelength range. However, at λ=3.9 µm, the ER shows a maximum peak of 1025 dB/mm. This is due to the strong coupling between the TE core mode and the surface-plasmon (SP) mode at the GST/dielectric interface in the crystalline phase. Therefore, the reported modulator shows high ER, very low IL at a compact device length of 50 µm which is a good candidate for integrated photonic devices.

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