Optical switching in multilayer structures based on Ge$_2$Sb$_2$Te$_5$

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Abstract. In this work, we have studied the phase switching in structures based on the Ge$_2$Sb$_2$Te$_5$ (GST) composition and their optical parameters of reflectivity and transmissivity at 1550 nm wavelength after exposure to the pulse of nanosecond laser at 403 nm wavelength. We investigated 24 nm GST single-layer structure and found about 50% optical losses due to the double reflection and transmission at 1550 nm radiation. To achieve the least optical losses, we added additional SiO$_2$, Si and Si$_3$N$_4$ layers to the structure. This allowed reducing optical losses up to 5 and 4% for absorption and undesirable reflection, respectively, for the amorphous GST layer, and 16 and 5% for absorption and undesirable transmittance, respectively, for the crystalline GST layer.

1. Introduction

Currently, systems of integrated optics are actively developing. Their widespread use is limited by high energy consumption, low switching speed, large sizes, large-signal delays, double-conversion of information from optical to electric signals and backward. The 1550 nm wavelength is a conventional standard for telecommunication systems. The chalcogenide glassy semiconductors of the Ge$_2$Sb$_2$Te$_5$ (GST) composition at the 1550 nm wavelength have the refractive index $n$ being different for GST in amorphous and crystalline states (see figure 1a). Besides, these materials have reversible, fast, and low-energy phase transitions. At present, these GST properties are used in integrated devices, IR-receivers based on meta-structures, optical disks etc. Moreover, the topical task is a fully optical routing (control) of optical signals that can be implemented in the following way.

Significant difference of the refractive index at the 1550 nm wavelength (see figure 1a) greatly influences reflectivity and transmissivity (see figure 1b) of the GST material that can be used to control the information carrying signal (to control the probe or information laser).

At the 400 nm wavelength (see figure 1a), the GST layer has a rather high extinction ratio $k$ in both amorphous and crystalline states. This property greatly affects material absorbing properties, therefore, 400 nm radiation pulses (of the pump or control laser) can be used for the effective control of the phase state switching from the amorphous state into the crystalline one and vice versa and, thus, to switch the information signal into the set directions (see figures 1c, 1d).

Currently, the devices based on thin GST films developed to perform fully optical control of optical signals at 1550 nm wavelength show increased losses that is especially observed in integrated optic devices [1 – 3]. The main result of these papers is optical signal modulation with phase state variation of the GST film. However, rather high losses (~50%) of the optical signal caused by absorption, undesirable reflection or transmission of the electromagnetic wave have not been taken into consideration. Besides, these losses will lead to the appearance of secondary waves, which weaken the resulting wave at the system output. When producing a cascade of active optical elements, this will definitely lead to the formation of unoperating entire system.
Figure 1. Spectral (a) and optical (b) properties of GST in amorphous and crystalline states. Operating modes of fully optically controlled GST structure (c, d): reflection with the amorphous GST film (c); transmission with the crystalline GST film (d).

In this paper, we have focused our attention on optimization of optical element parameters for their following application in more complicated systems. For minimization of optical losses at 1550 nm irradiation, we have suggested to use a GST layer as a part of additional layers redistributing the electromagnetic wave field as required depending on the GST layer phase state. Operation principle of such additional layers is similar to the Bragg grating [4] improving parameters of the structure transmission or reflection. Difference is connected with the fact that the Bragg grating is effective for the structure with the layers with invariant complex refractive index. In our case, the GST layer can change its phase state and complex refractive index, however, parameters of additional layers are invariable. In this regard, parameters of additional layers cannot be calculated by means of the Bragg grating model.

Thus, this work was aimed on the decreasing of optical losses by the multilayer structure based on GST at 1550 nm irradiation, when it is transmitted (with amorphous GST layer) or reflected (with crystalline GST layer).

2. Experimental

The GST layers with the thickness of 24 nm has been formed on the quartz substrates by the magnetron sputtering. Complex refractive index of the GST layers was determined by the ellipsometry (Uvisel 2, Horiba). The nanosecond laser (Cube 403-100C, Coherent) with a 403 nm wavelength was used for a local change of the phase state in the GST layers. Local control of the phase state in GST layers was performed by means of the Raman scattering spectroscopy. Spectroscopy and atomic force microscopy of the GST layer areas after the laser irradiation were executed by means of the probe nanoscale laboratory (Ntegra-Spectra, NT-MDT SI). Reflecting and transmitting capabilities in local switched areas of the GST layer have been recorded by photodiodes (818-BB-21, Newport).

3. Results and discussion

We have compared the obtained results of the simulation with the results of experimental investigations, which were performed initially for determination of starting optical losses. Experimental studies were carried out for the GST layers with 24 nm thickness, and optimal parameters of the laser irradiation necessary for the reversible change of phase state for the GST layers were determined. The local areas of the GST layers were irradiated by the 403 nm laser, which led to their amorphization and crystallization. Amorphization was observed with the pulse duration $t = 10$ ns, period $T = 200$ ns and radiant exposure $H = 3.2 \pm 0.03 \text{ nJ/µm}^2$. Figure 2a shows an AFM image of the GST film area with switching of the phase state from the crystalline to the amorphous one. Local Raman spectroscopy of this area has shown that intensity of the peak A decreases with the Raman shift of 130 cm$^{-1}$ (see figure 2b). Authors of the paper [5] explained an appearance of the peak in this range due to the transit of Ge atom from the octahedral surrounding of Te atoms into the tetrahedral...
one and lowering of the rigidity of Ge-Te bonding. So, peak A in the amorphous phase corresponds to the peak A₁ of the vibrational mode of GeTe₄ₙGeₙ tetrahedrons (n = 1, 2) connected by summits. Peak B with Raman shift of 145 cm⁻¹ corresponds to the fluctuations of atomic bonding Sb-Te. Main configuration providing a peak in this range are Sb₂Te₃, (Te₂)Sb-Sb(Te₂), (TeSb)Sb-Sb(Te₂) [6].

![Figure 2. AFM images of 1.5 × 1.5 μm² switching film area after 403 nm laser pumping (a). Raman spectra of the local region of GST film in crystalline (solid line - 1) and amorphous (dashed line - 2) phase states (b). Peaks corresponding to vibrations of Ge-Te (peak A, 130 cm⁻¹) and Sb-Te (peak B, 145 cm⁻¹) bonds were indicated on spectra by letters A and B. Shifts of peaks A and B with transition from crystalline to amorphous phase state were indicated by arrows.](image)

Investigation reflectivity and transmissivity of the local areas (see figure 2b) of phase state switching in the GST films have shown sufficiently large optical losses of ~ 46% for 1550 nm irradiation. These losses can be summarized as following: 12 and 16% due to the absorption and undesirable reflection, respectively, for the amorphous area of the GST layer, and 23% for both due to the absorption and undesirable transmission for the crystalline area of the GST layer.

We have analyzed modern methods for calculation of multilayer structures [7, 8] in detail, developed the model and carried out simulation of the electromagnetic wave distribution (at its normal incidence) in the multilayer structure. This allowed to determine optimal parameters of the multilayer structure based on GST, which provide the lowest optical losses due to the transmission or reflection of the irradiation at the 1550 nm wavelength for the structure with the GST layer in the amorphous and crystalline states, respectively. Simulation was performed by means of software MathLAB, Mathcad, OptifDTD using Fresnel-Airy recurrence relations that allowed determining reflectivity \( R \) and transmissivity \( T \) of the structure. For the normal incidence of an electromagnetic wave, \( R \) and \( T \) of a multilayer structure were determined by the following recurrence Airy relations [7]:

\[
R = \left| r_{m-1,N+1} \right|^2, \quad T = \left| r_{m-1,N+1} \right|^2 \frac{n_{N+1}}{n_{m-1}},
\]

\[
r_{m-1,N+1} = \frac{r_{m-1,m} + r_{m,N+1} \cdot e^{i \beta_m}}{1 + r_{m-1,m} \cdot r_{m,N+1} \cdot e^{i \beta_m}}, \quad \tau_{m-1,N+1} = \frac{\tau_{m-1,m} \cdot \tau_{m,N+1} \cdot e^{i \beta_m}}{1 + r_{m-1,m} \cdot r_{m,N+1} \cdot e^{i \beta_m}}
\]

where \( r_{m,N} \) and \( \tau_{m,N} \) are reflection and transmission coefficients, starting with the medium \( m-1 \) and ending with the medium \( N+1 \); \( m, N \) are layer numbers (\( m < N \)); \( \tilde{n}_m \) is complex refractive index of the medium material \( m \); \( h \) is layer thickness of the medium material \( m \); \( \lambda \) is vacuum wavelength; \( r_{m-1,m}, \tau_{m-1,m} \) \( r_{N+1,N+1} \) \( \tau_{N+1,N+1} \) and \( \tau_{m-1,m} \) \( \tau_{N+1,N} \) \( \tau_{N+1,N} \) \( \tau_{N+1,N+1} \) \( \tau_{N+1,N+1} \) are the Fresnel reflection and transmission coefficients, respectively, for adjacent mediums.

The plot in figure 3a show that simulation of the double layer structure (24 nm GST / 410 nm SiO₂) has similar to the experimental data results with sufficiently large optical losses for 1550 nm irradiation (3 and 11 % due to the absorption and undesirable reflection for the amorphous GST layer, respectively, and 24 % for both due to the absorption and undesirable transmittance for the crystalline GST layer). After addition of Si, SiO₂, Si₃N₄ layers, the six-layer (100 nm SiO₂ / 110 nm Si / 90 nm SiO₂ / 50 nm GST / 160 nm SiO₂ / 190 nm Si₃N₄) structure tends to obtain ideal parameters and have
lower optical losses (see figures 3b, 3c). The most satisfactory result was obtained for the six-layer structure (100 nm SiO₂ / 110 nm Si / 90 nm SiO₂ / 50 nm GST / 160 nm SiO₂ / 190 nm Si₃N₄). In particular, optical losses are reduced to 5% for absorption (Aₐ = 100 – ℜₐ – ℑₐ) and 4% for undesirable reflection (ℜₐ) for the amorphous GST layer, and 16% for absorption (Aₐ = 100 – ℜₐ – ℑₐ) and 5% for undesirable transmittance (ℑₐ) for the crystalline GST layer in comparison with the double layer structure. Losses non-linearly depend on the GST layer thickness h with local extremum close to 50 nm, which is the optimal thickness value h (see figure 3b).

Figure 3. Simulated dependences of reflectivity ℜ and transmissivity ℑ on the GST layer thickness h in the amorphous (ℜₐ, ℑₐ) and crystalline (ℜₐ, ℑₐ) states: (a) for the double layer structure; (b) for the six-layer structure; (c) for the ideal six-layer structure (GST: ₐ = 3.8; ₐ = 9.5); results of the investigation of complex refractive index  for the GST layers (ₐ = 3.8 + 0.6i; ₐ = 6.3 + 1.2i) obtained by the ellipsometry method were used for the simulations (figures 3a, 3b).

The obtained result can be explained by the following way. After fall of the 1550 nm electromagnetic wave on 100 nm SiO₂, this wave and arisen secondary waves suffer multiple reflections in multilayer structure. Layers 100 nm SiO₂, 110 nm Si and 90 nm SiO₂ perform functions of antireflective coatings and transmit secondary waves up to the GST layer. At the crystalline GST layer waves are reflected and pass in the opposite direction. In the amorphous GST layer waves pass through it and reach the following layers. Layers 160 nm SiO₂ and 190 nm Si₃N₄ are antireflective, so, the wave easily passes through them. Due to such mechanism of 1550 nm wave distribution, the multilayer structure achieves improved reflective or transmittive parameters depending on the GST layer phase state.

4. Conclusion
Thus, as a result of the simulation and experimental investigations, the multilayer structure based on the GST layer, which minimizes optical losses in comparison with double layer structures, was suggested. Construction of complex photonic crystal structures based on such multilayer structures will allow performing fully optical routing of optical signals in integrated optic systems.

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