Phase change material tuned metamaterials

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This paper assesses the suitability of GeTe-Sb$_2$Te$_3$ materials for tuning resonances in optical filters. At wavelengths beyond 2 μm the large change in the real part of the refractive index can be exploited to tune the resonance of Au-GST-Au square arrays. In contrast in the near-infrared, the change in imaginary component of the GST refractive index can be used to tune interferences at Al-GST interfaces.

1. Introduction

Arguably, the most useful and well-studied phase change materials exist along the GeTe-Sb$_2$Te$_3$ pseudobinary tie-line. These alloys were developed for re-writable optical data storage, and they are now the active materials in phase change electrical random access memory[1]. Data storage devices exploit the substantial change in optical and electronic properties between the amorphous and crystalline structural phases of GeTe- Sb$_2$Te$_3$ alloys. Data storage is accomplished by heating the amorphous material above its FCC crystallization temperature. The material is switched back to the amorphous phase by heating the material above its melting point and then quenching it into the amorphous structure. Typically a nanosecond-order laser or Joule current pulse is used to switch the material[2]. Although the material can also be amorphised with picosecond order pulses[3].

The objective of this work is to explore the potential of chalcogenide phase change materials for other applications in photonics; that is applications beyond data storage, such as non-volatile tuneable metamaterial filters and/or modulators.

2. Principle

GeTe-Sb$_2$Te$_3$ alloys exhibit an enormous change in refractive index in the visible and infrared frequencies. As an example, the refractive index of Ge$_2$Sb$_2$Te$_5$ (GST) in the FCC and amorphous states is shown in figure 1. This optical contrast stems from the delocalization of electrons along p-p bonds in the crystal phases[4]. These delocalized electrons are readily polarized by an EM-field and hence the refractive index is large. When the material is amorphised the long and medium range order in the crystal is lost and this inhibits long-range alignment of p-p bonds. The electrons become localized at their atoms and are no longer easily polarized by electromagnetic fields, thus the refractive index is reduced substantially[4]. Indeed, in the mid-infrared at λ=3 μm, the real part of the refractive index, n, is reduced from 6 to 4 whilst the imaginary component of refractive index, k, is almost zero in both structural states. That is, the material is almost non-absorbing. In the visible the change in absorption becomes more significant than the change in n. The crystalline state is significantly more absorbing than the amorphous state due to the enhanced optical transition matrix elements that result from resonant bonding in the crystalline state[4].

It is clear from figure 1 that GST presents two different mechanisms to enable active photonics: (1) exploring the significant change in k at visible frequencies, or (2) exploiting the large change in n in the mid-infrared. These two mechanisms and their limitations will be discussed here.
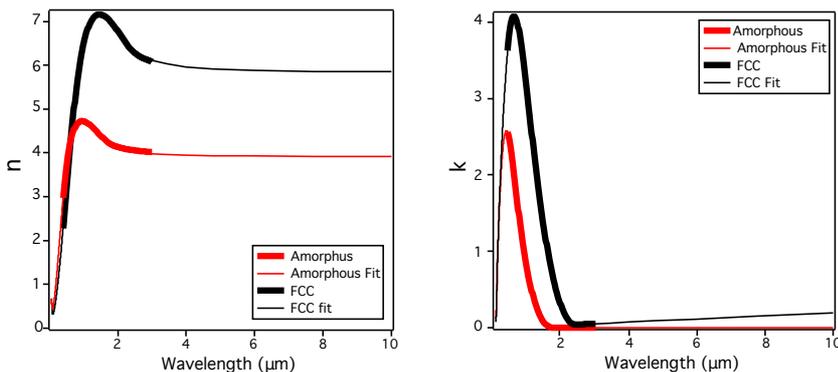

Figure 1: The refractive index (n) and extinction coefficient (k) as a function of wavelength for Ge2Sb2Te5 in the amorphous (red) and FCC (black) states.

3. Experiment

To show that the absorption properties of GeTe- Sb_2Te_3 alloys can be used to tune a reflective filter, we deposited a GST/Al layered structure on top of a Si substrate. Light reflecting from a dielectric—metal interface undergoes a non-π phase shift, and this leads to a strong interference effect within the GST film[5,6].

This is possible despite the GST being orders of magnitude thinner than the wavelength of light. The strong interference effect relies on a substantial proportion of the light reflecting back from the Al layer to the GST-Air interface. Crystallizing the GST increases the absorption of the light and therefore the strongest absorption occurs at longer wavelengths where the extinction coefficient, k, is smaller, see figure 1b. Figure 2(a) shows that a 48 nm thick amorphous GST film deposited on 100 nm of Al provides almost perfect absorption at $\lambda=1.1$ µm. Crystallizing the film shift this absorption resonance to $\lambda=1.4$ µm, where k is lower.

To show how the change in the real component of refractive index can be used to tune the reflected spectrum we need to design filters for the infrared, where k is almost zero. We have simulated an Au square array deposited on a GST—Au layered structure[7]. The square array has a pitch of 1 µm and a square size of 0.9 µm. The thicknesses of the top Au squares, the GST layer, and the Au bottom layer are 40 nm, 40 nm, and 80 nm respectively. At resonance this type of structure concentrates the electric field in the apertures between the Au squares and in the GST layer. This scenario causes displacement current loops through the GST layer between the top Au squares and the bottom Au layer. The displacement current loops cause a magnetic dipole moment that interacts strongly with the incident magnetic field[7]. In effect the structure allows simultaneous excitation of both electric and magnetic resonances, which in turn cause a strong absorption, even when GST's extinction coefficient is very small. Changing the real part of the refractive index of GST red-shifts the resonance condition to longer wavelengths, from 2.23 µm in the amorphous state to 2.46 µm in the crystalline state. As can be seen from figure 1(b) this effect is not due to the change in extinction coefficient because k~0 in both the crystalline and amorphous structural states at this wavelength.
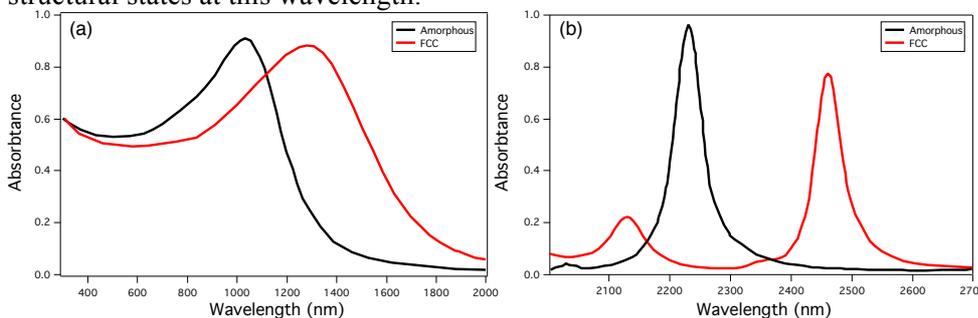

Figure 2: Absorption spectra for (a) GST/Metal layered structure and (b) an Au square array, GST, Au structure. Black curves are for amorphous GST and red curves are for FCC GST [6,7].

4. Conclusion

We have shown that changing either the real or imaginary component of the GST refractive index can be used to tune the resonant frequency of metamaterial filters. Reflective filters are less technologically relevant than transmissive filters, which can be placed in front of detectors. Our next challenge is, therefore, to develop tuneable transmissive filters, and this requires new forms of low-k phase change materials.

References
[1] M. Wuttig and N. Yamada, Nature Mater. 6(11), pp. 824–832, 2007.
[2] J. K. Behera et al. Opt. Mater. Express 7, pp. 3741–3759, Oct 2017.
[3] L. Waldecker et al. Nat Mater 14, pp. 991–995, 07 2015.
[4] J. Robertson et al. Thin Solid Films 515(19), pp. 7538–7541, 2007.
[5] M. A. Kats et al. Nat Mater 12, pp. 20– 24, 01 2013.
[6] W. Dong et al. J. Phys. Chem. C 120(23), pp. 12713–12722, 2016.
[7] T. Cao et al. J. Opt. Soc. Am. B 30, pp. 1580–1585, Jun 2013.