The 27th Iranian Conference on Optics and Photonics (ICOP 2021), and the 13th Iranian Conference on Photonics Engineering and Technology (ICPET 2021).University of Sistan and Baluchestan, Zahedan, Iran, Feb. 2-4, 2021

کد مقاله : ۱-۵۴۵-۱۰-A

# نانوسوئیچ پلاسمونیک مبتنی‌بر GST با روش مدار معادل در ناحیه فروسرخ نزدیک

**طاهره پناهی، نجمه نزهت**

**دانشکده مهندسی برق، دانشگاه صنعتی شیراز**

**T.panahi@sutech.ac.ir, nozhat@sutech.ac.ir**

**چکیده– در این مقاله، یک نانوسوئیچ پلاسمونیک متشکل از یک نانودیسک نقره که بر روی یک لایه GST قرار گرفته،در ناحیه فروسرخ نزدیک طراحی و شبیه‌سازی شده است. ماده تغییر فاز GSTبا تغییر دما، ساختار را تنظیم‌پذیر می‌کند. به‌دلیل تغییر قابل‌توجه در پیوند GST،هنگامی که از حالت آمورف به حالت کریستالی تغییر می‌کند، ضریب شکست آن به میزان قابل توجهی افزایش می‌یابد. تغییر در طیف جذب بین حالت‌های آمورف و کریستالی، منجر به قابلیت سوئیچینگ با نسبت خاموشی 10.3 dB در طول‌موج 1564 nm می‌شود. به منظور بهینه‌سازی عملکرد ساختار، تاثیر ضخامت GST، اندازه شعاع نانودیسک و زاویه تابش بررسی می‌شود. همچنین، روش تحلیلی مدار معادل برای تایید نتایج شبیه‌سازی استخراج شده است. نتایج به‌دست آمده در این پژوهش، قابلیت بالای استفاده از مواد تغییر فاز به‌ویژه GST، به عنوان یک ماده مناسب برای استفاده در ادوات مختلف فوتونی قابل تغییر با انرژی کارآمد، از جمله جاذب‌ها، حافظه‌های چند سطحی و ادوات رنگی در فرکانس‌های نوری را نشان می‌دهد.**

**کلید واژه**–پلاسمون سطحی، روش مدار معادل، سوئیچ پلاسمونیک، ماده تغییر فاز GST.

# GST-based Plasmonic Nano-switch with Equivalent Circuit Model in Near-infrared Region

**TaherehPanahi, NajmehNozhat**

**Department of Electrical Engineering, Shiraz University of Technology**

**T.panahi@sutech.ac.ir, nozhat@sutech.ac.ir**

**Abstract-**In this paper, a plasmonic nano-switch that is composed of a silver nanodisk located on the GST layer is designed and simulated in the near-infrared region. The GST phase change material adjusts the structure by changing the temperature. Due to the significant change in the GST bond, when it varies from amorphous state to crystalline one, its refractive index increases remarkably. A change in the absorption spectrum between amorphous and crystalline states leads to switching capability with the extinction ratio of10.3 dB at the wavelength of 1564 nm. In order to optimize the structure performance, the effects of GST thickness,nanodisk radius size and incident angle are investigated. Also, the equivalent circuit method is derived to confirm the simulation results. The obtained results demonstrate the high capability of using phase change materials specially GST, as a suitable material for use in various energy-efficient switchable photonic devices such as absorbers, multi-level memories and color devices at optical frequencies.

Keywords: Equivalent Circuit Model, Phase Change Material GST, Plasmonic Switch, Surface Plasmon.

## 1.Introduction

Plasmonics is a special part of fascinating field of nanophotonics and it is related to the interaction of electromagnetic waves and oscillations of free electrons of metal nano-structures [1]. When the interface of metallic structure is large enough, surface plasmons (SPs) can propagate, which are called propagating surface plasmons (PSPs), otherwise they oscillate at their own place as localized surface plasmons (LSPs) [2].

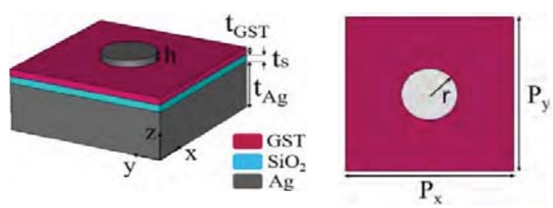
In recent years, research in plasmonics has attracted great attention due to easy access to fabrication methods especially for implementation of nanostructures [1]. A lot of plasmonic structures have been proposed and investigated due to their potential applications in switching [3], nanosensing [2], optical modulation [4], etc.

The most common techniques for SP excitation are utilizing charged particles or highly focused beams and various optical techniques for phase-matching such as prism and grating couplings. The excited wavelengths of PSPs and LSPs are very sensitive to the geometrical parameters of plasmonic nanostructures [1]. For excitation of SPs, it is necessary to use high efficiency materials. Gold and silver are the most common metals for effective excitation. Combination of noble metals with some new materials can increase the excitation of SPs. Utilizing phase change materials (PCMs) such as chalcogenide, vanadium oxide, and liquid crystalprovide a possibility for new plasmonic devices in a wide range of optical frequencies. After structural transition, PCMs exhibit a large change in their dielectric constant. Thus, PCMs can make photonic structures adjustable [5]. GST (germanium-antimony-tellurium or $Ge_2Sb_2Te_5$) is another PCM that has amorphous and crystalline states. The GST film is initially in amorphous state. When it is annealed above 160 °C, it turns into crystalline state [6]. Based on this unique features, GST can be used in various switchable photonic devices such as absorbers [7], chiral metamaterials [8], and color devices [9].

In this paper, a plasmonic nano-switch based on adjustable material of GST with more than 95% absorption efficiency is proposed in the near-infrared region. The effects of geometrical parameters on the absorption and switching performances are investigated. Also, the analytical method of equivalent circuit model is studied to verify the simulated results of the proposed plasmonic nano-switch.

## 2. Structure Geometry and Simulation Method

The three dimensional (3D) schematic view of the proposed nano-switch is shown in Fig. 1. It consists of three layers over the metallic substrate. The GST layer is separated from the substrate by the $SiO_2$ layer. A silver (Ag) nanodisk with thickness of h=30 nm and radius of r=200 nm is placed on the GST layer. The dielectric constant of GST is chosen according to Ref. [3] and the experimental data of Refs. [10] and [11] are used for the Ag substrate and $SiO_2$ layer, respectively. The other parameters of the structure are given as follows: $t_{Ag}$=200 nm, $t_s$=10 nm, $t_{GST}$=10 nm, $P_x$= $P_y$= 600 nm.




(a) (b)

Fig. 1: Schematic view of a unit cell of the proposed GST-based plasmonic nano-switch. (a) 3D view and (b) top view.

To simulate the proposed structure, the CST Microwave Studio software based on the finite element method (FEM) with tetrahedral mesh has been used. A x-polarized plane wave stimulates the structure along the z-axis. The open boundary condition along the z direction and periodic boundary condition (PBC) along x and y directions have been used. The absorption (A) can be calculated by A=1-R-T [12], where R and T are the reflection and transmission coefficients, respectively.

## 3. Results and Discussion

Figure 2 illustrates the absorption spectrum of the proposed structure with a nearly perfect absorption peak at λ=1564 nm in amorphous state. According to Fig. 2, when GST is in amorphousand crystalline states, the absorptions above 95% and near-zero are achieved, respectively. Thus, by changing the temperature, this structure can be considered as a switch with the extinction ratio of $\eta = 10\log(A_{a-GST} / A_{c-GST}) = 10.3$ dB. $A_{a\text{-}GST}$ and $A_{c\text{-}GST}$ are the absorption values at amorphous and crystalline states, respectively.

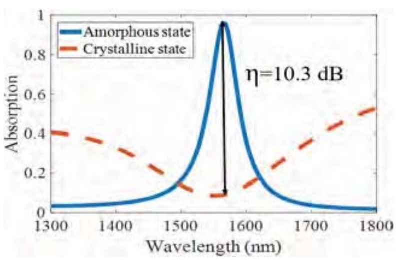
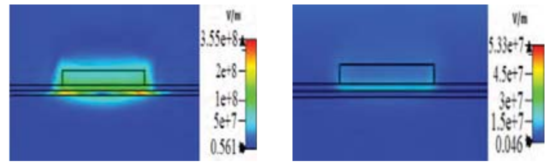



Fig. 2: Absorption spectra of the proposed GST-based plasmonic nano-switch.

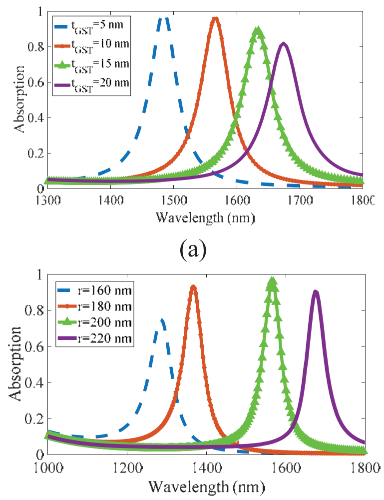
The electric field distributions of the proposed structure at λ=1564 nm, which corresponds to the resonance wavelength in amorphous state of the GST layer are shown in Fig. 3. When GST is in the amorphous state, the LSPs are created at the interface of silver and dielectric film. While GST is in the crystalline state, the LSPs are more concentrated in the GST layer. This phenomenon leads to a large difference in their effective refractive index and the switching performance of the GST-based structure can also be seen.

Here, the absorption spectrum of the proposed structure for different values of structural parameters is studied. According to Fig. 4, by increasing the thickness of GST layer ($t_{GST}$), the interaction of LSPs between the GST layer and Ag film and so the absorption are decreased. Although, by decreasing $t_{GST}$ the absorption peak reaches almost one, but in the crystalline state, the absorption increases and the extinction ratio decreases. As a result, the thickness of the GST layer cannot be considered too small. Increasing the radius of nanodisk (r), results in larger resonator size in the structure. Therefore, the resonance wavelength shifts to the higher value.



(a) (b)

Fig. 3: Electric field distributions of the proposed GST-based nano-switch when GST changes from (a) amorphous state to (b) crystalline state.




(b)

Fig. 4: Absorption spectra of the proposed GST-based nano-switch for different values of (a) GST layer thickness ($t_{GST}$) and (b) nanodisk radius (r).

Moreover, the absorption spectra for different incident angles $(\theta)$ are shown in Fig. 5. It is obvious that the structure is almost insensitive to the incident angle up to 50°. After that, the absorption peak decreases.

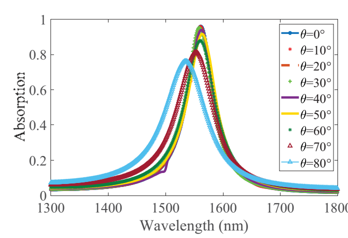



Fig. 5.Absorption spectra of the proposed GST-based nano-switch for different incident angles.

## 4. Equivalent Circuit Model

The method of equivalent circuit model has been studied to verify the simulated results of the proposed plasmonic nano-switch. The extracted equivalent circuit model is shown in Fig. 6. The dielectric parts of the structure are modeled by the transmission line with the characteristic impedance of $Z = \eta_0 / \sqrt{\varepsilon_r}$, the propagation constant of $\beta = 2\pi / \lambda_g$ and the electrical length of $E = 2\beta \times t$, where $\eta_0$, $\lambda_g$, $\varepsilon_r$, and $t$are the free space impedance, guided wavelength, relative permittivity and thickness of the dielectric layer, respectively. The impedance of the Ag layer can be obtained from $Z_{Ag} = R_{Ag} + j\omega L_{Ag} = \sqrt{\frac{\omega\mu}{2\sigma}}(1+j)$ formula, where $\sigma$ and $\mu$ are conductivity and permeability of the metallic layer, respectively [12]. A parallel branch is used to model the nanodisk and air.

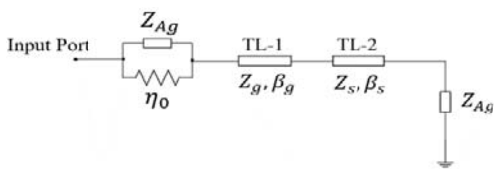



Fig. 6: The equivalent circuit model for proposed structure.

The initial values of the circuit model parameters are shown in Table I. According to Fig. 7, there is a good agreement between the simulation and circuit model results.

Table I. The parameters values of the equivalent circuit model of the proposed structure.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $R_{Ag}$ | 32.9 Ω | $Z_s$ | 258.48 Ω |
| $L_{Ag}$ | 0.334 fH | $E_s$ | 6.71° |
| $Z_g$ | 95.62 Ω | $E_g$ | 18.15° |

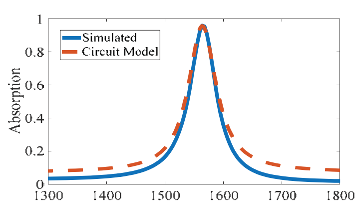



Fig. 7: The simulated and circuit model absorption spectra of the proposed structure.

## 5. Conclusion

In this paper, a GST-based plasmonic nano-switch including silver nanodisk located on the GST layer has been proposed. The switching performance of the suggested structure is based on the change in the absorption spectrum, when the GST state changes from amorphous to crystalline. An almost good switching performance has been achieved with the extinction ratio of 10.3 dB at λ=1564 nm.Also, the equivalent circuit model has been derived to confirm the simulation results.

## References

**[1]** S. A. Maier, *Plasmonics: Fundamental and Applications*, Springer, 2007.

**[2]** G. Li, X. Chen, O. Li, C. Shao, Y. Jiang, L. Huang, B. Ni, W. Hu, and W. Lu, “A novel plasmonic resonance sensor based on an infrared perfect absorber,” *J. Phys. Appl. Phys*., vol. 45, pp. 205102-1-5, 2012.

**[3]** H. Zhang, L. Zhou, L. Lu, J. Chen, and B. M. A. Rahman, "Non-volatile optical switch based on a GST-loaded directional coupler," 2018 IEEE 3rd Optoelectronics Global Conf. (OGC), Shenzhen, pp. 68-71, 2018.

**[4]** F. Moradiani, M. Seifouri, K. Abedi, and F. G. Garakhili, “High extinction ratio all-optical modulator using a vanadium-dioxide integrated hybrid plasmonic waveguide,” *Plasmonics*, 2020. doi: 10.1007/s11468-020-01276-7.

**[5]** N. Kumar, A. Rua, J. Aldama, K. Echeverria, F. Fernandez, and S. Lysenko, “Photoinduced surface plasmon switching at $VO_2$/Au interface,” *Opt. Express*, vol. 26, pp. 13773-13782, 2018.

**[6]** K. K. Du, Q. Li, Y. B. Lyu, J. C. Ding, Y. Lu, Z. Y. Cheng, and M. Qiu, “Control over emissivity of zero-static-power thermal emitters based on phase-changing material GST,” *Light: Sci. Appl.*, vol. 6, p. e16194, 2016.

**[7]** L. Zhang, Y. Wang, L. Zhou and F. Chen., “Tunable perfect absorber based on gold grating including phase-changing material in visible range,” *Appl. Phys A,* vol. 125, pp. 1-7, 2019.

**[8]** G. Dong, C. Qin, T. Lv, M. Sun, et al., “Dynamic chiroptical responses in transmissivemetamaterial using phase-change material,” *J. Phys. D:Appl. Phys*, vol. 53, pp. 1-13, 2020.

**[9]** P. Hosseini, C. D. Wright, and H. Bhaskaran., “An optoelectronic framework enabled by low dimensional phase-change films,” *Nature*, vol. 511, pp. 206-211, 2014.

**[10]** S. Babar and J. H. Weaver,” Optical constants of Cu, Ag, and Au revisited,” *Appl. Opt,* vol. 54, pp. 477-481, 2015.

**[11]** I. H. Malitson “Interspecimen comparison of the refractive index of fused silica,” *J. Opt. Soc. Am,* Vol. 55, pp 1205-1208, 1965.

**[12]** M. Nejat and N. Nozhat, "Design theory and circuit model of wideband tunable and polarization-insensitive terahertz absorber based on graphene", *IEEE Trans. Nanotechnol.*, vol. 18, pp. 684-690, 2019.