Electro-Optic Tuning of Terahertz Yagi-Uda Antenna Arrays through Liquid Crystal Reorientation

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ABSTRACT

This study examines the tuning capabilities in Yagi-Uda antenna arrays for terahertz frequencies through electro-optic modulation using nematic liquid crystals. The investigated structure consists of a periodic 2D array of Yagi-Uda antennas on a dielectric substrate. The substrate is covered below with a metallic ground plane, and further beneath is a vacuum layer. The space above the antenna array is filled with a nematic liquid crystal, which is bounded above by a glass substrate. Strong anchoring boundary conditions for the liquid crystal ensure an initial pi/2 twist configuration. The plane wave is normally incident on the Yagi-Uda antenna arrays while following the Mauguin regime. The application of an external electric field perpendicularly to the substrates reorients the liquid crystal director from its initial twisted state to a homeotropic state, resulting in the change of polarization of the light when it reaches the antenna array. The numeric simulations of the mentioned structure were conducted in COMSOL Multiphysics, and have shown that varying the applied voltage in the mentioned structure enables the tunability of the plasmonic resonances in the antenna array. The tunability frequency interval was found to span approximately 7–12 THz, with the absorbance tuning range reaching 95% of the incident intensity. By leveraging the electro-optic properties of nematic liquid crystals, the research highlights a controlled method for tuning THz antenna arrays, presenting a solution for the advanced control of antenna properties in THz applications.

Keywords: Yagi-Uda antenna arrays, liquid crystal, electro-optic modulation, polarization control, dynamic tuning.

1. INTRODUCTION

Metamaterials have attracted increased attention due to their remarkable properties, including negative refraction, cloaking, advanced lensing, dynamic tunability in plasmon-induced transparency, and perfect absorption [1-3]. Perfect metamaterial absorbers, particularly those employing antenna configurations such as Yagi-Uda structures, demonstrate highly directional resonance properties and facilitate near-perfect absorption at specific wavelengths [4-6].

The integration of liquid crystals (LCs) into metamaterials greatly expands their functional capabilities, allowing for the real-time control of resonance frequency and amplitude [7-9]. In the presented work, we study investigate the tuning of 2D Yagi-Uda micro-antenna arrays within the THz spectral range using nematic LCs. We present a structural layout enabling control of absorbance and reflectance by up to 90%, requiring approximately 2.5 Volt voltage input. This underscores the potential for highly efficient and adaptable metamaterial designs.

2. MATERIALS AND METHODS

The structure consists of a periodic 2D Yagi-Uda antenna array on a dielectric substrate (Fig. 1a). The Yagi-Uda micro-antennas are filled above with a nematic LC, bounded on the other side by a semi-infinite layer of glass. A thin metal foil forming a ground plane is underneath a dielectric slab to enhance the absorption of the antenna. The material below the ground plane is assumed to be a vacuum for simplicity. The normally incident y-polarized light enters the structure from the glass medium propagates in the negative z-direction to reach the Yagi-Uda antenna array. The LC director has an initial $\pi/2$ twist configuration with a pretilt angle of 1°.

Liquid Crystals Optics and Photonic Devices, edited by Ibrahim Abdulhalim, Camilla Parmeggiani,
Proc. of SPIE Vol. 13016, 1301603 · © 2024 SPIE
0277-786X · doi: 10.1117/12.3017639

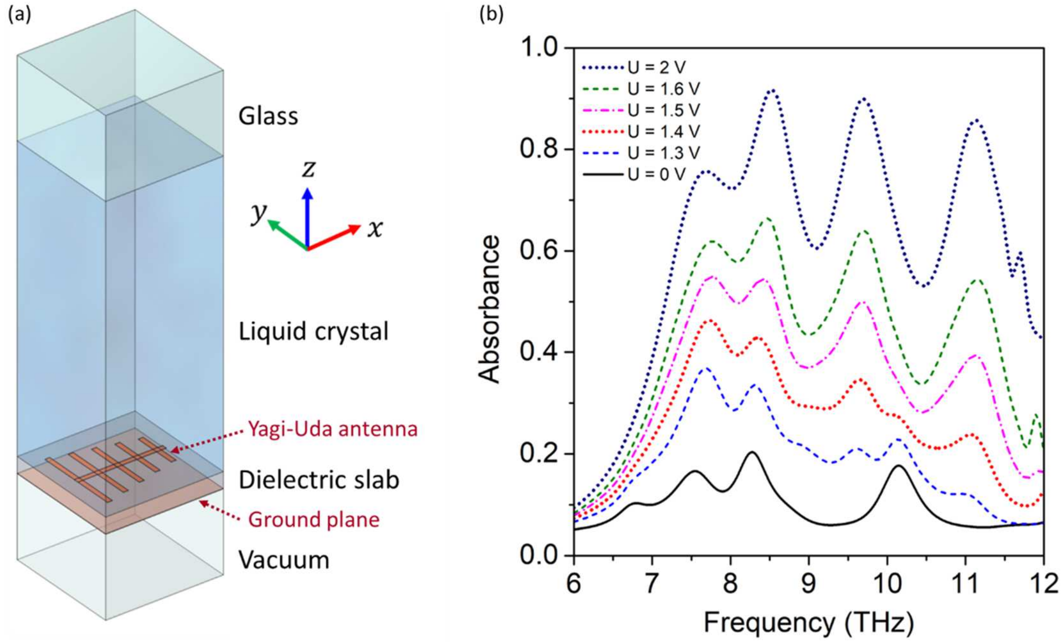

Figure 1. Unit cell of the structure under study (a). Absorbance profiles at different voltages applied to the LC cell (b).

The LC layer has a thickness of $L = 50\ \mu m$ to facilitate the Mauguin regime. The ordinary and extraordinary indexes of the LC are $n_o = 1.7$ and $n_e = 2.2$, respectively [10, 11]. The refractive index of glass was also set to 1.7 to avoid additional reflections at the LC – glass interface. The Yagi-Uda antenna array and the ground plane are copper, with the real and imaginary parts of refractive indexes corresponding to those reported in [12]. The antenna consists of a base and five perpendicular arms, each having a width of 0.5 μm. Together they form the antenna of a length of $L_0 = 9\ \mu m$, with arms on both sides of the base having the lengths of 4, 3.5, 3, 2.5, and 2 μm, respectively. The thickness of the antenna and the ground plane is 35 nm. The lateral periodicity is defined by the square unit cell with the size of 10 μm. The dielectric slab has the thickness of 1.6 μm and is made out of a material such as flame-retardant glass epoxy FR4 [13] with a relative permittivity of 4.3 and a loss tangent of 0.025 [6]. The elastic coefficients of the LC are $K_{11} = 11.1 \times 10^{-12}$ N, $K_{22} = 5.9 \times 10^{-12}$ N, and $K_{33} = 17.1 \times 10^{-12}$ N [14]. The LC has the parallel and perpendicular components of the static dielectric permittivity of $\epsilon_{\parallel} = 19.28\ \epsilon_0$ and $\epsilon_{\perp} = 5.21\ \epsilon_0$, respectively [14], where ϵ_0 denotes the vacuum permittivity.

3. ABSORBANCE SPECTRA

Figure 1b shows the absorbance spectra of the Yagi-Uda micro-antenna arrays at different values of the voltage applied perpendicular to the substrates. Within the 6–12 THz frequency range, distinct peaks characterize the resonances in the absorbance spectra. These resonances correspond to the excitation of different plasmonic modes within the Yagi-Uda antennas. When no voltage is applied (Fig. 1b, black line), the light is x-polarized near the antenna due to the initial y-polarization being rotated within the Mauguin regime, causing the absorbance profile to have peaks at 7.5, 8.3, and 10.1 THz, reaching 20% in amplitude. When the voltage is applied, the director reorients toward the homeotropic orientation, disabling the Mauguin regime. This results in the light being y-polarized when it reaches the Yagi-Uda antennas. In this case, the absorbance increases to 50–60%, with distinct peaks at 7.7, 8.5, 9.7, and 11.1 THz of up to 90% in amplitude (Fig. 1b, dark blue line). The absorbance control range is determined by the position and intensity of plasmonic peaks for different light polarization, as well as by the fulfillment of the Mauguin regime. At larger frequencies around 11 THz, higher voltages of 1.4–2.5 volts are required to disable the Mauguin regime, while 1.1–1.9 volts are sufficient at lower frequencies near 7 THz.

4. CONCLUSIONS

This study demonstrates the design of an LC-controlled Yagi-Uda micro-antenna array, where the reorientation of the LC can be used to control the absorbance across the frequency range of 7–12 terahertz. This technique achieves an average absorbance tunability range of 50–60% over the specified frequency interval, reaching up to 90% at 11 THz. The operational voltages are found to be approximately 1.1–1.9 volts at lower frequencies around 7 THz, and 1.4–2.5 volts at higher frequencies near 11 THz. This research enhances the potential applications of LCs in dynamically controlling the resonance features of Yagi-Uda metamaterial absorbers, expanding the possibilities for real-time modulation of their properties.

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