Laser generation in a Tamm plasmon structure controlled by a nematic liquid crystal

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ABSTRACT

The possibility of controlling laser generation in a layered structure using a nematic liquid crystal (NLC) is theoretically studied. This structure consists of a thin layer of silver (Ag), a layer of NLC doped with a light-absorbing dye, and a distributed Bragg reflector (DBR). The spectral dependencies of the reflection, transmission, and absorption coefficients of light by such a structure, as well as the enhancement coefficient of the light field in the NLC layer in the DBR's band gap, are calculated. The narrow dips in the reflection coefficient and the peaks in the transmission coefficient are caused by the excitation of Tamm plasmon-polaritons (TPPs) at the Ag-NLC interface. The excitation of TPPs is accompanied by a significant increase in the intensity of the light field in the NLC volume compared to the intensity of the incident light. With an increase in the thickness of the NLC, the density of Tamm-plasmon peaks increases. It is shown that in the case of an optical anisotropy $\Delta n = n_e - n_o = 0.3$, the control range for the position of the plasmon peaks reaches up to 100 nm. Temporal luminescence pulses for pump pulses of different power settings are also presented. Above threshold, luminescence in the system manifests itself in the form of a series of short pulses with their amplitude and duration monotonically decreasing over time. Increases in the peak power of the pump cause the duration of the individual luminescence pulses to decrease.

Keywords: nematic liquid crystal; Tamm plasmon polariton; distributed Bragg reflector; band gap; light reflection; light transmission; laser generation

1. INTRODUCTION

Localized electromagnetic modes at metal-distributed Bragg reflector interfaces, also known as Tamm plasmon-polaritons (TPPs), have attracted increased attention due to their unique optical properties [1, 2]. Unlike typical surface plasmons, TPPs can be excited without additional components such as prisms or gratings. Sensitivity to dielectric parameters and significant local field amplification make TPP applicable in sensor technologies, optical devices, and laser generation [3, 4].

Liquid crystals (LCs) can be introduced to the Tamm-plasmonic system in order to dynamically control its optical responses under various external conditions. This provides avenues to modulate TPP characteristics, particularly when using cholesteric liquid crystals (CLCs) or rugate filters (RFs) [5,6]. Liquid crystals enhance laser technology by enabling tunable lasing properties through external influences such as external fields [7], temperature [8], and mechanical stress [9]. Nematic LCs (NLCs) are particularly notable for their ability to dynamically control laser outputs within a Fabry-Perot cavity, achieving wavelength control ranges up to 30 nm [10] and precision tuning within 0.008 nm [11].

Fluorescent dyes combined with liquid crystals serve as an effective active laser medium. Particularly, dye-doped CLCs, exploiting their natural one-dimensional photonic crystal configuration, significantly improve laser performance [12-14] and offer extensive tunability over 300 nm [15]. Additionally, incorporating dye-doped NLCs in distributed feedback-based lasing systems has shown substantial promise in enhancing dynamic wavelength control [16]. In this work, we explore the theoretical potential for tunable lasing in a Tamm-plasmon hybrid structure consisting of metal, dye-doped NLC, and DBR elements.

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2. LASER GENERATION

The system under study features a NLC layer sandwiched between a metal (Ag) film and a DBR, supported by a dielectric substrate. This structure is illustrated in Figure 1a, where the DBR is made of alternating layers of TiO_2 and SiO_2, with respective refractive indices $n_{TiO_2} = 2.46$ and $n_{SiO_2} = 1.48$. The substrate refractive index is 1.529, while NLC ordinary and extraordinary indices are 1.48 and 1.63, respectively. The thicknesses of the metal film and NLC are correspondingly 60nm and 3287nm, and the DBR layers' thicknesses are 51nm (SiO_2) and 96nm (TiO_2), with the DBR comprising of 12 layers.

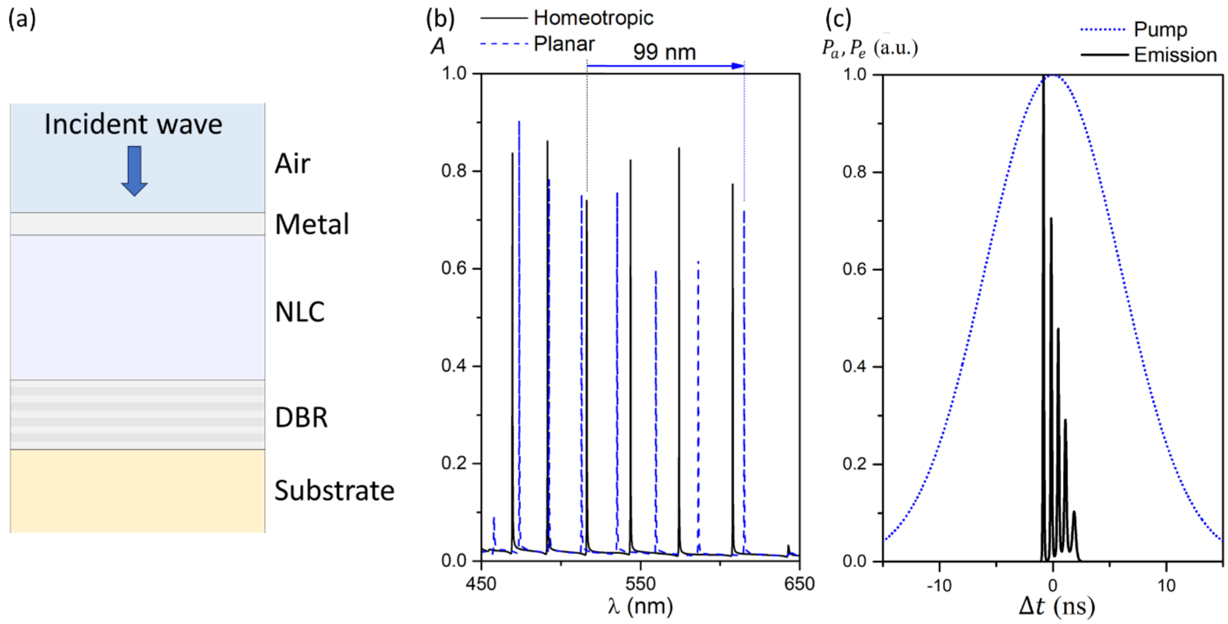

Figure 1. Tamm-plasmonic structure of metal film-NLC-DBR under study (a); absorbance spectra for homeotropic (solid line) and planar (dashed line) LC director orientations (b); pump (dotted line) and laser emission (solid line) temporal profiles (c).

The NLC director is initially homeotropically aligned. A plane normally incident monochromatic wave enters the structure from air, penetrating sequentially through the metal, NLC, and into the DBR and substrate, undergoing multiple reflections. Numerical results on the spectral dependencies of the absorption coefficient A are shown in Figure 1b. Two extreme cases of NLC layer orientation, homeotropic and planar, were considered in order to assess the overall impact of NLC reorientation, as well as to estimate the Tamm plasmon tuning range. The reorientation of the NLC layer from homeotropic (solid line) to planar (dashed line) orientation induces a shift in the wavelength of the plasmonic peaks by around 100 nm, showcasing the dynamic control over the plasmonic response without significant changes in the overall spectral distribution of peak amplitudes.

In dye-doped NLC, the presence of dye results in a negative imaginary part of the refractive index of the dye-doped NLC. This in turn can lead to the reflection coefficient R becoming larger than unity [17]. This leads to a significant increase in the amplification of the light field within the dye-doped NLC to the extent that the intensity of the reflected light becomes larger than the intensity of the incident light (seed) wave, which enables spontaneous laser generation. Further simulations on laser generation were conducted by solving the rate equations [12, 14, 17], resulting in the temporal profiles of laser pulses as presented in Figure 1c. The laser generation threshold occurs at a pump power of approximately 7.4 W, equivalent to a pumping intensity of 9.2 MW/cm^2. Above the lasing threshold, the system emits a sequence of pulses with decreasing amplitude. The latter can be attributed to the gradual depletion of singlet states through transfer processes to triplet states (from which radiative emission is prohibited). The first intense luminescence pulse precedes the pump pulse maximum in the supra-threshold regime, with individual pulse duration narrowing as pump power increases. This behavior, along with the temporal profiles of laser emission in this hybrid Ag-NLC-DBR structure, aligns with the findings from prior research on CLC lasers with distributed feedback [12, 14, 17].

3. CONCLUSIONS

In this work, laser generation in an Ag-NLC-DBR structure was theoretically studied. The numerical analyses reveal that the TPP resonances at the Ag-NLC interface, manifested as dips and peaks in optical spectra, are significantly influenced by the NLC layer's thickness and orientation. Notably, reorienting the NLC director from homeotropic to planar state shifts the plasmon peaks by approximately 100 nm. Introducing a dye into the NLC affects the amplification but not the overall distribution of light intensity, maintaining the potential for substantial tunability within the dye's fluorescence band.

Our results demonstrate that for pump peak powers exceeding laser threshold, luminescence in the system manifests itself in the form of a series of short luminescence pulses with their amplitude and duration monotonically decreasing over time. Variation of pump peak power impacts individual luminescence pulse duration and amplitude, with a trend toward shorter pulses at higher pump powers. Overall, the Ag-NLC-DBR structure's is shown to be capable for substantial intensity amplification and real-time lasing control, highlighting its potential in optoelectronics and photonics for precise laser control and wavelength manipulation.

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