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ADE-FDTD-based Numerical Simulations for the Development of Novel Laser Devices

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ABSTRACT

This paper discusses on our resent studies on the numerical simulation of lasing dynamics in cholesteric liquid crystal as a one dimensional photonic crystal. On the basis of ADE-FDTD method, which incorporates finite-difference time-domain (FDTD) method with auxiliary differential equations (ADEs) such as rate equation in a four level energy structure and equation of motion of polarization, we have successfully reproduced circularly polarized lasing at the edge energy of the stop band. The threshold pumping rates for the lasing can be evaluated. Our computational scheme may also be quite useful as a development tool for fabricating more efficient laser cavity systems

1. INTRODUCTION

Recently, numerical analysis of lasing dynamics in various types of microcavity laser systems, such as random laser [1-3], photonic crystal (PC) laser [4, 5], distributed Bragg reflector laser [6, 7], have been reported. In these reports, ADE-FDTD method [8], which incorporates finite-difference time-domain (FDTD) method with auxiliary differential equations (ADEs) such as rate equation in a four level energy structure and equation of motion of polarization, has been utilized. The ADE-FDTD approach offers the following superior advantage [1]. One can follow the evolution of the electromagnetic (EM) field and electron numbers in the time-domain and emission spectra can also be analyzed by Fourier transforming the time-domain EM field. One can also obtain a time-dependent field distribution in and out of the microcavities. We have been working on numerical analysis of lasing dynamics in cholesteric liquid crystal (CLC) as a one dimensional (1D) PC on the basis of ADE-FDTD method [9-12]. Our technique may offer great advantage for a deep understanding of underlying mechanism of lasing dynamics in CLC and may also be quite useful as a development tool for the development of more efficient laser cavity systems.

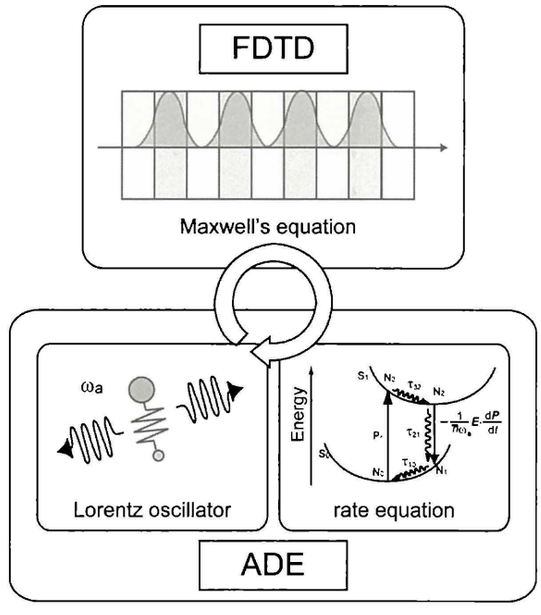

Fig.1 : Schematic representation of numerical analysis of lasing dynamics on the basis of ADE-FDTD method

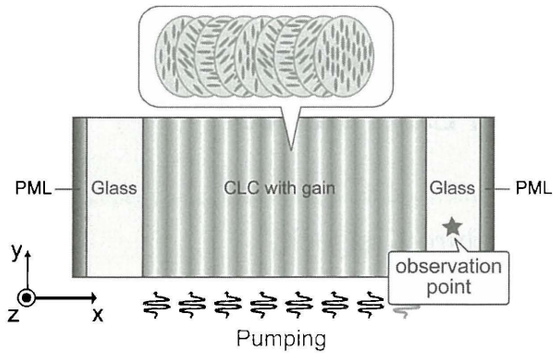

Fig. 2: Schematic representation of CLC laser cavity system.

2. NUMERICAL SIMULATION

In the ADE-FDTD method for the analysis of lasing dynamics, FDTD method, which solves Maxwell's equations in microcavity laser systems in a flop-frog manner, is coupled with ADEs such as the rate equations in a four level energy structure and the equation of motion of polarization as schematically shown in Fig. 1. In order to simulate optically anisotropic media like CLCs, dielectric permittivity in Maxwell's equations should be represented as a tensor. Detailed description of procedures of our numerical analysis can be found in ref [9-12].

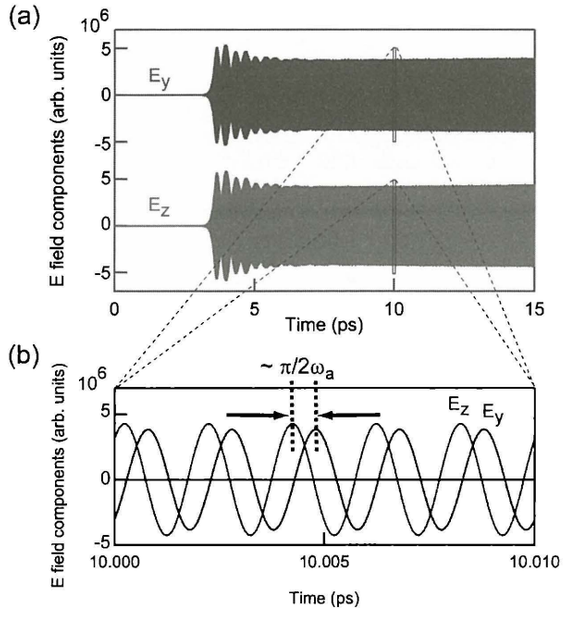

Fig. 3: (a) Transient response of E_y and E_z field components observed at the glass. Pumping rate P_r is 1.0×10^{10} s^{-1}. (b) Steady-state response at around 10 ps.

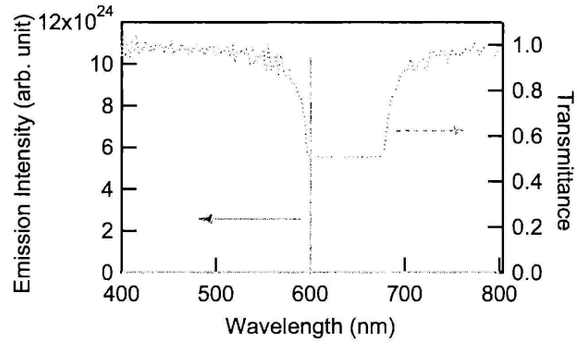

Fig. 4: Emission spectrum pumped at P_r = 1.0×10^{10} s^{-1} and transmittance of CLC with 400 nm helical pitch.

3. RESULTS AND DISCUSSIONS

Some kinds of LCs such as CLCs which have chirality in their molecular structures form periodic helical structure in a self organized manner, and if the pitch of their helix is in the range of the wavelength of light they can work as PCs, thus as microcavity for the lasing. Since Kopp and his coworkers reported on the experimental observation of lasing at the edge energy of the stop band from laser dye-doped CLC [13], numerous studies have been carried out. However, to the best of our knowledge, there have been no reports on the numerical simulation of lasing in this system. Here we report on our recent work on the numerical analysis of lasing dynamics in a 1D system with periodic helical structure. Analyzed 1D system is schematically represented in Fig. 2.

In Fig. 3 (a), monitored transient responses of E_y and E_z fields are shown. The pumping rate is P_r = 1.0×10^{10} s^{-1}. After a short time (~ 3 ps), rapid evolution of both fields are observed, and after several oscillations, they reach a steady state. In Fig. 3 (b), the steady-state responses of E_y and E_z fields are shown. A sinusoidal response, which might be due to monochromatic lasing emission, is observed. It can also be recognized that the oscillation of orthogonal field components is out of phase and shifted by approximately one-quarter of $2\pi/\omega_a$ and thus corresponds to the relative phase delay of a quarter-wavelength. This implies that lasing emission is circularly polarized, which may be attributed to the distributed feedback mechanism unique in the helical structure of CLCs and therefore indicates that CLC is indeed working as a laser cavity.

Time-domain steady-state responses are Fourier transformed for the evaluation of the power spectrum of the emission. In Fig. 4, the emission spectrum at a pumping rate of P_r = 1.0×10^{10} s^{-1} is shown. The

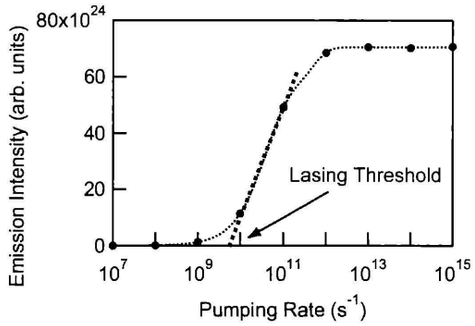

Fig. 5: Emission intensity at the lasing peak wavelength as a function of pumping rate P_r.

transmission spectrum is also shown for comparison. A sharp lasing peak appears at the higher energy edge of the stop band above the threshold pumping.

In Fig. 5, the emission intensity at the lasing peak is shown as a function of pumping rate P_r. A steep increase in the emission intensity above around $P_r = 8.0\times10^9$ s^{-1} can be recognized. The threshold pumping rate for lasing can be identified, as shown by the black dotted line. The reduction of the lasing threshold has been one of the main subjects in the research field of CLC lasers. Refining device architecture may realize further lowering of the lasing threshold. As shown above, one can simulate threshold pumping rates using our computational scheme. Our method may offer a superior advantage to device design.

4. CONCLUSIONS

We have successfully reproduced circularly polarized lasing at the edge energy of the stop band in CLC on the basis of ADE-FDTD method. Our technique can be used to deeply understand the underlying mechanism of lasing dynamics in CLC and can also be used as a tool for the development of more efficient laser cavity systems.

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