Optics Communications 285 (2012) 1900–1904

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Temperature tunable random laser using superconducting materials

Abbas Ghasempour Ardakani [a], Mehdi Hosseini [a], Ali Reza Bahrampour [a,*], Seyed Mohammad Mahdavi [a,b,**]

[a] Department of Physics, Sharif University of Technology, Tehran, Iran
[b] Institute for Nanoscience and Nanotechnology, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 10 October 2011
Received in revised form 9 December 2011
Accepted 10 December 2011
Available online 22 December 2011

Keywords:
Random laser
FDTD method
Superconductor layer

ABSTRACT

We propose that spectral intensity of superconductor based random lasers can be made tunable by changing temperature. The two fluid model and wavelength dependent dispersion formula have been employed to describe the optical response of the superconducting materials. Random laser characteristics have been calculated using the one dimensional FDTD method. Our simulation results reveal that the emission spectrum can be manipulated through the ambient temperature of the system. It is observed that transition from metal phase to pure superconducting phase leads to the enhancement of the laser emission. Furthermore, spatial distribution of the fields in one dimensional disordered media is very sensitive to the system temperature.

1. Introduction

Lasing in disordered media is a subject of growing interest in recent years and has been widely studied both theoretically and experimentally [1–15]. So far many models have been constructed for investigation of random lasers [6–10]. Among them, a time dependent model was presented by Jiang et al. in which Maxwell–Bloch equations are solved numerically by using FDTD method for one dimensional (1D) case [11], and it was extended by Sebah and co authors to two dimensional (2D) case [12]. Many properties of random lasers can be explained by this model [11–15]. To use random lasers, the method used to externally control random laser line-width, intensity and wavelength are important. Tuning of the output of random laser with temperature was demonstrated by Lawandy et al. using a dye dissolved in polymethylmetalcrylate matrix [16]. Another scheme was also reported by K. Lee et al.; they used a novel system based on the lower critical solution temperature (LCST) mixture containing a high gain dye [17]. The LCST materials can be reversibly transformed from a transparent state to a highly scattering colloid, as the temperature is increased above room temperature (41 °C) [17]. So scattering length and diffusion coefficient in disorder active system based on this material as a scatterer are temperature dependent and tuning the line-width of random laser emission is possible. Wiersma et al. made a liquid crystal based random laser, in which minor change in the temperature leaded to significant change in the laser emission behavior [18]. In this paper, a novel random laser using superconducting materials has been proposed that its emission behavior is temperature dependent. Superconducting materials were used in photonic crystal (PC) previously [19–23]. Due to the damping of electromagnetic waves in metals, metallic elements in photonic crystal were replaced with superconducting (SC) elements. The dielectric function of SC depends on superconducting gap and SC state which can vary with external parameters such as temperature and magnetic fields. As a result the optical properties of PC can be controlled externally. Using superconducting materials in random lasers provides a method for control of laser emission with temperature. Here, random lasers based on SC element are investigated and lasing emissions are calculated at different temperatures. Our results reveal that lasing spectrum and electric field wave functions depend on temperature and emission intensity is enhanced as superconductive properties increases.

Remaining parts of this paper are organized as follows. In Section 2, we introduce a general form of time dependent theory in one-dimensional case in the presence of dispersive superconducting element. In Section 3, we calculate spectral intensity and spatial distribution of electric fields for different temperature. Finally, the paper is concluded in Section 4 with some conclusions.

2. Theoretical model

For simplicity, we calculated one-dimensional (1D) random lasers which could reveal qualitative properties of 2D and 3D random lasers. As shown in Fig. 1, our 1D system is made of binary layers consisted of two dielectric materials. The black layer with dielectric constant of $\varepsilon_{SC}(\omega)$ and random variable thickness of d_{sn}, simulate the superconducting materials (YBCO). The white layer in Fig. 1, with dielectric constant of $\varepsilon = 4$ and random thickness of d_{gn} simulates active or gain media (Nd:YAG). The value of d_{sn} and d_{gn} is randomly selected in the range [300 nm–480 nm]. The system consists of 76 pairs of binary layers, and the length of system is 60 micrometer.

* Corresponding author.
** Correspondence author to: S.M. Mahdavi, Institute for Nanoscience and Nanotechnology, Sharif University of Technology, Tehran, Iran.
E-mail addresses: bahrampour@sharif.edu, bahrampour.alireza@yahoo.com (A.R. Bahrampour), mahdavi@sharif.edu (S.M. Mahdavi).

0030-4018/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2011.12.052

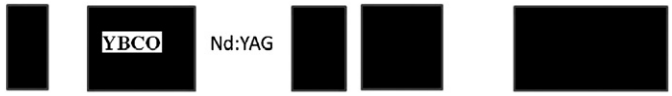

Fig. 1. Schematic for one dimensional random system in which the blue and white layers simulate the SC and active layers respectively.

For isotropic, non-magnetic and active media, the Maxwell's equations are

$$\frac{\partial E(x,t)}{\partial x} = \mu_0 \frac{\partial H(x,t)}{\partial t} \tag{1}$$

$$\frac{\partial H(x,t)}{\partial x} = \frac{\partial D(x,t)}{\partial t} + \frac{\partial P_{\text{transition}}(x,t)}{\partial t} \tag{2}$$

where $P_{\text{transition}}$ is the polarization density due to the specific atomic transition from which gain or amplification is obtained; by setting $P_{\text{transition}} = 0$ the above equations can be used for passive medium; D is the electric displacement.

In the SC materials for simplicity, we consider the electromagnetic property by using the two-liquid Gorter–Kazimir model which describes the system as an admixture of two independent carrier liquids, the super and the normal electrons [22–25]. The dielectric constant of the superconductors is a complex function of the exciting frequency [22–26]:

$$\varepsilon(\omega) = 1 - \frac{e^2}{m\varepsilon_0}\left[\frac{n_n \tau^2}{1+\omega^2\tau^2} + \frac{n_s}{\omega^2}\right] - i\frac{e^2}{m\varepsilon_0}\frac{n_s \tau}{\omega(1+\omega^2\tau^2)} \tag{3}$$

where e, m, n_n, n_s and τ are the electron charge, electron mass, normal electron concentration, super electron concentration and relaxation time of normal electron, respectively. The normal electron concentration ($n_n(T) = n_t t^\beta$) is an increasing function of the normalized temperature ($t = T/T_c$), while the super electron concentration ($n_s(T) = n_t(1-t^\beta)$) is a decreasing function of t [27–29]. Here n_t is the total electron concentration of the superconductor; T_c is the critical temperature of the superconductor and β is about 2 and 4 for the high temperature (HTS) and low temperature superconductors (LTS), respectively. The superconductor gap is a decreasing function of temperature and approaches to zero as the temperature goes to the critical value T_c. Below the critical temperature ($T \ll T_c$), at the frequency corresponding to the superconductor gap, the superconductor resistance has a sharp threshold. The superconductor gap of YBCO is about 30 meV [30], and the absorption coefficient which is proportional to imaginary part of the right hand side (RHS) of the Eq. (3) is approximately zero for frequencies below the superconductor gap and increases for photon with energy larger than the superconductor gap. However variation of imaginary part of RHS of Eq. (3) is negligible compared to its real part. This effect makes superconductor as a suitable material for tunable photonic crystals in the near infrared region [31,32]. The superconductor threshold wavelength is the vanishing refractive index wavelength. For the YBCO high temperature SC, the threshold wavelength is in the range of (1260 nm to 1880 nm) [31,33,34], which are in the infrared region. In the vicinity of the optical band gap of superconductor the absorption energy is not negligible and has the significant effects on the optical behavior of superconductor. The optical gap of YBCO is in the range of (1.4 eV–1.9 eV) [31,33,34] which is larger than the photon energy of Nd:YAG lasers. So, in the near infrared region, the dielectric constant of the superconductor layer is approximately expressed as:

$$\varepsilon_{SC}(\omega) = 1 - \omega_p^2\left\{\frac{\alpha}{\omega^2} + \frac{1-\alpha}{\omega[\omega - i\gamma]}\right\} \tag{4}$$

where $\alpha = 1 - t^\beta$ is the superconducting fluid fraction; $\omega_p = \sqrt{e^2 n_t / m\varepsilon_0}$ is the plasma frequency corresponding to the total electron density. It should be noted that some authors have applied Eq. (4) for tunable SC photonic crystals in the visible frequencies [19,35]. The dielectric constants of two layers in one-dimensional random system are given as:

$$\varepsilon(x,\omega) = \begin{cases} 4 & \text{for active medium} \\ \varepsilon_{SC}(\omega) & \text{for supercinducting medium} \end{cases} \tag{5}$$

Therefore the dielectric constant of the superconducting materials can be tuned by changing the temperature. In order to simulate the superconductor layers as a dispersive media in FDTD, Eq. (5) must be put into the sampled time domain. The detail of transformation from frequency to time domain is given in the appendix.

The active medium (Nd:YAG) is considered as a four-level system [36]; the third level (N_3) and the second level (N_2) are called the upper and lower lasing level respectively. The life time of levels N_4, N_3 and N_2 are τ_{43}, τ_{32} and τ_{21} respectively. The rate equations for this system are as follows [11,37]:

$$\frac{dN_4(x,t)}{dt} = P_r N_1(x,t) - \frac{N_4(x,t)}{\tau_{43}} \tag{6}$$

$$\frac{dN_3(x,t)}{dt} = \frac{N_4(x,t)}{\tau_{43}} - \frac{N_3(x,t)}{\tau_{32}} + \frac{E}{\hbar\omega_l}\frac{dP_{\text{transition}}}{dt} \tag{7}$$

$$\frac{dN_2(x,t)}{dt} = -\frac{N_2(x,t)}{\tau_{21}} + \frac{N_3(x,t)}{\tau_{32}} - \frac{E}{\hbar\omega_l}\frac{dP_{\text{transition}}}{dt} \tag{8}$$

$$\frac{dN_1(x,t)}{dt} = -P_r N_1(x,t) + \frac{N_2(x,t)}{\tau_{21}} \tag{9}$$

where N_i ($i = 1$–4) are the population density in level i; P_r is pumping rate which is proportional to the pump power and is assumed to be constant here. The $\omega_l = (E_3 - E_2)/\hbar$ is lasing frequency between level 2 and 3; the stimulated emission is given by the term $\frac{E}{\hbar\omega_l}\frac{dP_{\text{transition}}}{dt}$. For single electron case, the polarization density is obtained from the following equation of motion [11,37]:

$$\frac{d^2 P_{\text{transition}}(x,t)}{dt^2} + \Delta\omega_l \frac{dP_{\text{transition}}(x,t)}{dt} + \omega_l^2 P_{\text{transition}}(x,t) = k\Delta N(x,t)E(x,t) \tag{10}$$

where $\Delta\omega_l = 1/\tau_{32} + 2/T_2$ is full width at half maximum linewidth of atomic transition; T_2 is the mean time between dephasing events; $\Delta N = N_2 - N_3$ is the population inversion and $k = 6\pi\varepsilon_0 c^3/\omega_l^2\tau_{32}$ is a constant. The amplification line-shape derived from Eq. (10) is Lorentzian homogeneously broadened when ΔN is independent of time.

The values of those parameters that will be used in our simulation are taken as: $T_2 = 2\times10^{-14}$ s, $\tau_{43} = 1\times10^{-13}$ s, $\tau_{32} = 1\times10^{-10}$ s, $\tau_{21} = 1\times10^{-11}$ s, $N = \sum_{i=1}^{4} N_i = 3\times10^{24} m^{-3}$ and $\nu_l = \omega_l/2\pi = 2.82\times10^{14}$ Hz ($\lambda_l = 1064$ nm) [36]. The life time of level 3 is chosen shorter than real value in order to reduce the computation times as performed in previous works [12]. The high temperature superconductor YBCO is considered in the following calculations. Its parameters in normal state are $\omega_p = 1.67\times10^{15}$ rad/s, $\gamma_p = 1.34\times10^{13}$ rad/s and $T_c = 91$ K [38]. When the active system is pumped, the electromagnetic fields can be calculated using different methods such as transfer matrix method, effective refractive index method and FDTD method. In this paper, we apply FDTD method to solve Eqs. (1–2) and (6–10). In order to simulate an open system, the Liao method is used to impose absorbing boundary condition (ABC). Due to numerically solving of Maxwell's equations, boundary conditions for the fields at the interface between two media are automatically satisfied. The space and time increment are taken to be $\Delta x = 10$ nm and $\Delta t = 1.67\times10^{-17}$ s respectively. A