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The spatial coherence properties of the spontaneous emission in the one-dimensional strong random system with gain

Lina Shi[a,b,*], Chengfang Li[a], Xunya Jiang[b], Peijun Yao[b]

[a]*Department of Physics, Wuhan University, Wuhan 430072, People's Republic of China*
[b]*National Key-lab of the Functional Material, Shanghai Institute of Microsystem and Information Technology, CAS, Shanghai 200050, People's Republic of China*

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Abstract

By using the finite difference time domain method, the spatial coherence properties of the spontaneous emission in the one-dimensional strong random system with gain are investigated in detail. Results show that the coherence properties improve slowly with the increase of the system length at low pump rates. And at high pump rates the coherence properties obviously become better after a certain system length. While at very high pump rates it is a non-monotonic function of the system length, there exists the best coherence at a certain system length. These behaviors are explained by Lamb theory and scaling theory. Our study may be helpful to the designing of random lasers.

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Keywords: Coherence; Wave propagation in random media; Mesoscopic structure; Random laser

1. Introduction

Lasing action in random gain media has received considerable attention [1–10] in the past decades. Not only this phenomenon has potential commercial applications due to their small volume, easy fabrication, and low cost, but also people can research the Anderson localization with lasing action in random gain media. The optical coherence of emitted light is the basic characteristic of lasers. Experiments [7,8] have demonstrated that light emitted from random amplifying media exhibits coherence properties characteristic of true laser light. Florescu and John [9] have studied the coherence properties of the random laser using a novel approach based on a generalized master equation formalism. While the quantitative investigation on the coherence properties of the spontaneous emission or the amplified spontaneous emission in random lasers, has not been performed yet. In this paper, we introduce random sources to simulate the spontaneous emissions and use the finite difference time domain (FDTD) method to study the coherence of the spontaneous emissions in random system with gain. We first calculate the ensemble averaged spatial coherence degree and the coherence length in one dimensional (1D) system, and then study their dependence on the system length L at different pump rates.

In many theoretical methods [1,3,6,12] describing lasing in random media, the FDTD method has been shown to be a convenient tool in studying random laser modes in 1D and 2D cases. This method was first introduced for 1D case by Jiang and Soukoulis [6] and then extended to 2D case by Vanneste and Sebbah [11]. The characteristics of the random laser such as the dynamic response and relaxation oscillations were investigated [13–16] by using this theory. In all these studies, the sources in numerical simulations are the coherence sources and so the coherence properties of

*Corresponding author. Department of Physics, Wuhan University, Wuhan 430072, People's Republic of China. Tel.: +86 13916757828; fax: +86 2768752569.

E-mail addresses: shilina@mail.sim.ac.cn (L. Shi), chfli@whu.edu.cn (C. Li).

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the spontaneous emission cannot be calculated. In this paper, we introduce the spontaneous emission sources by a current noise in Maxwell equation and study the coherence properties of the spontaneous emission.

This paper is organized as follows. In Section 2 we briefly describe the structure, the spontaneous emission source we introduced and the essential steps of our numerical calculation. In Section 3 we analyze effects on coherence by the system length for different pump rates. A brief conclusion is given in Section 4.

2. The model of calculation

2.1. The structure

Our system is a 1D simplification of the real experiments [5,4] as shown in Fig. 1. The binary layers are made of dielectric materials with dielectric constants of $\varepsilon_a = 4\varepsilon_0$ and $\varepsilon_b = \varepsilon_0$, respectively. The layer shaded by red in Fig. 1 simulates scatterers with gain and its thickness is a random variable $a_n = a_0(1 + 2W\gamma)$, where $a_0 = 1\,\mu\text{m}$, W is the strength of randomness, and γ is a random value in the range $[-0.5, 0.5]$. Another layer simulates the free space and its thickness is also a random variable $b_n = a_0(1 + 2W\gamma)$, where a_0, W and γ have the same mean as the above. Obviously, this structure possesses periodic background. In this paper the random degree W is chosen to be 0.5 and according to the transfer matrix method we obtain that the localization length ξ_0 of this system is about 20 μm. And the random system we investigated contains 12–60 layers.

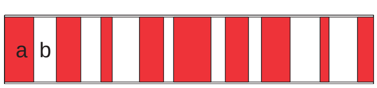

Fig. 1. Schematic for 1D random system. The red area denotes scatters with gain. The blank is the free space.

2.2. The source

To simulate the spontaneous emission in the real laser system, we introduce sources homogeneously distributed in the system. Within the semiclassical framework, spontaneous emission can be included in Maxwell's equation as a noise current [17]. Due to the periodic background the localized modes in gap region contain the devotion of both band gap and disorder. In order to exclude the band gap effect, the center frequency f_0 of radiation is chosen to be 1.5×10^{14} Hz, which locates at the center of the third band when $W = 0$. In order to cover more localized modes, every source has a large frequency width: $\Delta f_0 = 0.15 f_0$. An arbitrary source field in system versus the time is plotted in Fig. 2(a) and Fig. 2(b) is the spectral shape of the source electric field. Fig. 3 denotes the statistical distribution of our source which is a narrow band Gaussian noise. From Fig. 3 we can find that the source we introduce definitely has the characteristic of the spontaneous emission. Theoretically, every discrete grid point of the layers representing the gain medium, is a source that can generate spontaneous emission. Because this is very time consuming, we selected to use a finite number (20–60) of sources.

2.3. The calculation of coherence

An important descriptor of the spatial and temporal fluctuations of an arbitrary optical wave $U(r, t)$ is the cross-correlation function of $U(r_1, t)$ and $U(r_2, t)$ at pairs of positions r_1 and r_2 [18]: $G(r_1, r_2, \tau) = \langle U^*(r_1, t)U(r_2, t + \tau)\rangle$. This function of the time delay τ is known as the mutual coherence function. Its normalized form

$$g(r_1, r_2, \tau) = \frac{G(r_1, r_2, \tau)}{[I(r_1)I(r_2)]^{1/2}} \tag{1}$$

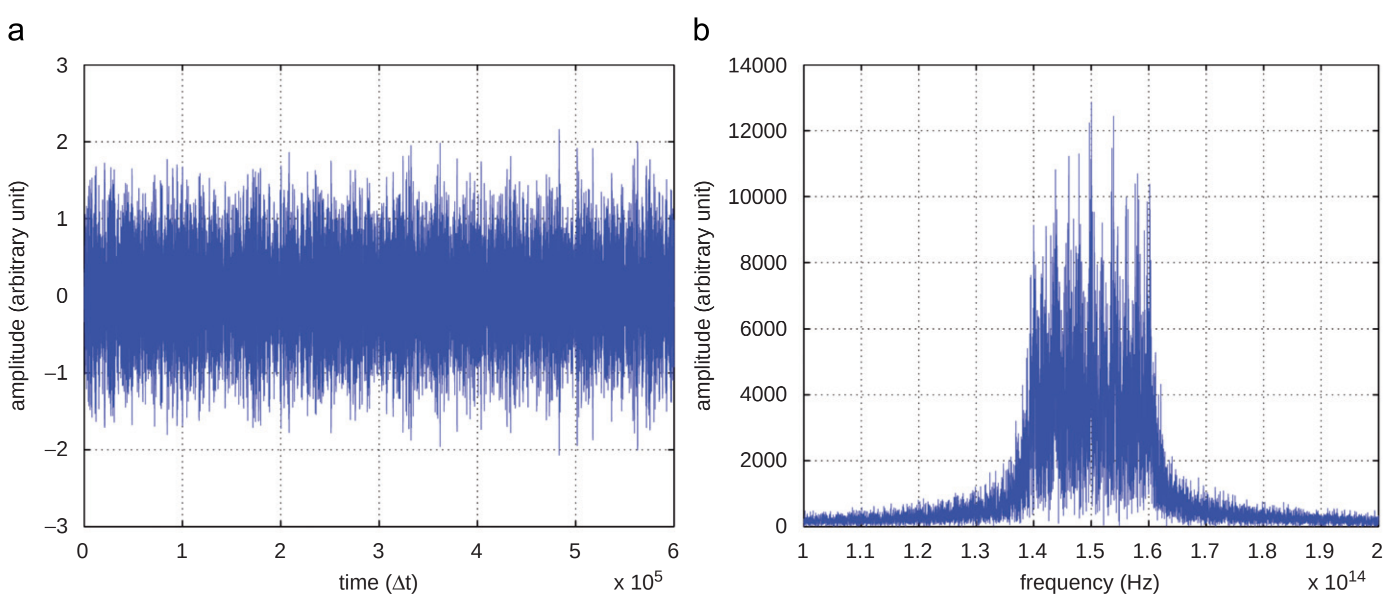

Fig. 2. (a) The field of the source versus the time. (b) The spectral shape.