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Critical behavior of nanoemitter radiation in a percolation material

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ABSTRACT

We studied the field radiation of disordered optical nanoemitters incorporated into three-dimensional (3D) spanning cluster in a percolation material. In supercritical state, the field intensity is large enough to produce a dynamic high-density coherent field. The resulting state becomes different for lossless and lossy mediums. For material with small losses the long-term coherence arises in the supercritical area close to the percolation threshold. As a result, the dynamic non-monotonic behavior of the field order parameter raises that allows to reach the optimal field intensity. This effect can allow optimization of the disordered optical nanostructures with incorporated radiating nanoemitters in various applications of information technology.

1. Introduction

The radiation of photons by disordered nanoemitters incorporated into three-dimensional (3D) clusters in percolation solids is an area of active research. At a small concentration of defects in such a system the number of clusters is insignificant. However, if the concentration of clusters exceeds a certain threshold value, then in the system it is formed spanning (infinite) cluster, penetrating the entire volume. This cluster qualitatively changes the properties of the medium and produces a generalized conductivity in the system which originally does not possess such a property. We studied the optical radiation of nanoemitters incorporated into such three-dimensional structures. In such a geometry, the spanning cluster serves as the "backbone", or a set of bonds, through which the field radiation of nanosources can flow.

Percolating systems are well-studied theoretically and also possess important applied perspectives: e.g., the creation of various solid-state filters on the basis of a porous medium. In the latter, the important aspect gives rise to identification of spanning cluster existence that may be realized by optical methods quickly and confidently. Numerous features of such mediums are well-studied in conducting environments, systems with complex magnetic structures, and in porous systems with a liquid or gas passing [1–8].

The percolation problem is concerned with elementary geometrical objects (spheres, sticks, sites, bonds, etc.) placed randomly in a d-dimensional lattice or continuum. The objects have a well-defined connectivity radius, and two objects are said to communicate if the distance between them is less than this radius. One is interested in how many objects can form a cluster of communication, and especially, when and how the clusters become infinite. A review of the dynamics of percolation clusters and of other fractals is given in [9].

Traditionally, light localization [10,11] and various interference effects [12–14] have been assisted by scatterers, such as powders [15–17] of dielectric or semiconductor materials, with dimensions comparable to the wavelength of light [18]. In such cases, the optical transport in systems of coupled porous (cavities) can already be considered by analogy with the "bond percolation" problem [19,20] in percolation theory [21].

The order parameter P_s in such a medium is defined as the ratio of the number of pores belonging to the spanning cluster to the general number of pores. It is obvious that P_s is distinct from zero only when exceeding the threshold concentration (0.311 for 3D case).

After formation of the spanning cluster, the opportunity to incorporate the nanoemitters through such the opened cluster structure becomes possible. It is important that the cross-section of clusters normally exceeds the field wavelength; therefore, such a network forms the open waveguide system by means of which the passage of an intensive laser short pulse behaves as the field pump. As a result, the two-level nanoemitters incorporated into such a cluster can be raised to the excited state. For simplification of the problem, we have used the natural assumption that nanosources are incorporated only in those clusters which have a connection with the entrance (input for laser pump) side of the

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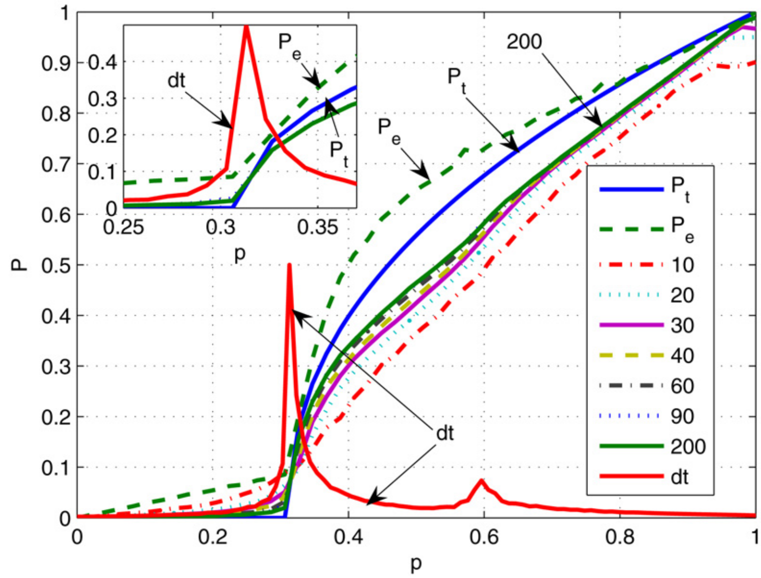

Fig. 1. (Color online.) The order parameter $P_s(p)$ (defined as the ratio of the number of pores in the spanning cluster to the total number of pores) as a function of the occupation probability p. Numerical simulations are made for different sizes of system with $L = 10, 20, 30, 40, 60, 90, 200$; $dt(p)$ is the time interval required to calculate correspondent value $P_s(p)$. In the inset, the area is shown close to the threshold p_{3D}. We observe that the percolation arises close to the value $p_{3D} = 0.31$. The dependence of the field order parameter $P_e(p)$ and $P_t(p)$ are shown also. See details in text.

sample. Since the spatial cluster structure in the medium does not change with time, the corresponding order parameter P_s is a static property of the system. However, the situation becomes more complicated for the case of radiating nanoemitters incorporated in such disordered structure.

The analysis of such a system consists of two steps, and in general it requires quite long computations. The first step deals with identification of the spanning cluster P_s as a function of probability p. In the second step, the field properties of radiating nanoemitters incorporated into the percolation structure (known from the first step) are calculated with the use of technique FDTD [22].

As a result of numerical experiments, we have found that at the supercritical concentration of disordered nanosources the intensity of the field radiation increases sharply. In the lossy medium, or for emitters with random phases, the field order parameter P_e has well-known static behavior. However, the situation changes essentially for the coherent radiated nanoemitters in materials with small losses due to arising of field long-term coherence. As a result, the dynamic non-monotonic behavior of the field order parameter raises that allows to reach the optimal field intensity already at $p \sim 0.5$. This is our main result.

It is worth to note that the properties of photons in three-dimensional (3D) disordered percolation mediums in various geometries are an area of active research [23–25]. Nevertheless, the properties of radiation from artificial percolation 3D clusters is still studied insufficiently. Such an effect can be very promising for various applications (where the transmission state has to be controlled by concentration of the nanoemitters) incorporated into such a material. As far as the authors are aware, the critical properties of radiating nanosources incorporated into percolation medium has poorly been considered yet, though it is a logical extension of previous work in this area.

This Letter is organized as follows. In Section 2, the basic equations and our numerical scheme to study 3D static clusters are discussed. In Section 3, we study the dynamic field properties of radiated nanoemitters incorporated into the spanning cluster, which is considered in Section 2. Discussion and conclusions from our results are found in Section 4.

2. Numerical simulations of the 3D cluster structure

In this section, we focus on the geometrical properties of percolation clusters. We study a cubic (periodic) lattice embedded in a 3-dimensional (3D) medium. It is assumed that the probability p for each site of the lattice to be “occupied” is given, and we investigate the spatial distribution of resulting clusters over sizes and other geometrical parameters. We recall that a cluster here means a conglomerate of occupied sites, which communicate via the nearest-neighbor rule.

We assume that the distance between lattice nodes is l, and the radius of spherical defects (sites) is a. It is easy to see that in case $l\sqrt{2}/2 > a > l/2$, the nearest-neighbours approach can be used. This allows us to neglect (as a first approximation) the influence of the shape and the size of defects on the percolation threshold.

In our algorithm, the connectivity of defects is initially examined locally, so that, two defects (pores) produce a cluster if they have at least one edge in common. In such an approach, the spanning occurs when the size of the largest (spanning) cluster reaches the size of system. The rest of the cluster is referred to as a collection of “dead” or “dangling” ends. A dangling end can be disconnected from the cluster by cutting a single bond.

In a large enough sample, the internal topology is changed substantially at the critical concentration of defects. It seems to be quite possible that an intrinsic topological structure affects the dimensionality of the transition: the connectivity of a percolating network acquires the form of a fractal that allows studying the properties of such a systems only numerically. We draw special attention to the percolation threshold, at which an infinite cluster spans the lattice. It is worth noting that in the three-dimensional case, no percolation threshold is known exactly; only numerical data are available [25].

In our study first, we numerically calculated the value of probability p_{3D} (critical threshold) when the spanning 3D cluster emerges for the first time. Corresponding dependencies are shown in Fig. 1.

We observe from Fig. 1 that all curves indicate the percolation threshold in the vicinity $p_{3D} \approx 0.31$ that is known from 3D per-