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Light scattering in random planar structures supporting guiding modes

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ABSTRACT

We study light scattering by surface roughness assisted by excitation of guided modes in dielectric layers. The same roughness might result in a very different scattering efficiency depending on whether and how the guided modes participate in scattering. Enhanced scattering to modes with a different modal number and to modes propagating backward is predicted and observed.

1. Introduction

Study of light scattering in planar structures supporting guided modes confined in dielectric layers is important from practical point of view due to their application in optoelectronic devices used in communication and optical sensor systems. The scattering problem is also related to fundamental issues such as weak localization in two- and three-dimensional systems, local field enhancement resulting in giant nonlinear response, etc. Moreover, light scattering problem became attractive for the lasing in random media. It was rather surprising that random scattering and random trajectories of light waves not necessarily would result in de-phasing of the scattered waves [1].

Light scattering in waveguide grating structures has been studied by many researchers [2–8]. Various approaches like the Fourier–Bloch mode method [8] and the guided mode expansion methods [9] were developed in order to understand such effect. Moreover, the backscattered light that is induced by the waveguide surface roughness was also modeled for planar and channel waveguides [10,11]. In this paper we present an experimental evidence of enhanced scattering in two-dimensional systems. Namely, we show that a light wave that is confined to the guiding layer would more likely scatter to another guided wave rather than scattered out of the waveguide. We also show a case of interference-induced suppression of scattering out of the waveguide. It means that even in a random medium trajectory of scattered waves stays mainly in the plane of the waveguide. Intuitively, it would be easier to get closed trajectories in two dimensions compared to the three-dimensional case. Thus, the random lasers that are realized in planar waveguides will more likely show lower threshold and, due to light confinement in the waveguide, exhibit higher brightness. This justifies the importance of studying the scattering in planar waveguides..

2. Theory

Enhanced scattering itself is usually explained by stronger light intensity at the surface associated with excitation of guided modes. However, it is only a half of explanation. Really, the Fourier components of random surface roughness in general would produce relatively uniform scattering in wide range of angles. The field enhancement cased by excitation of guided modes can explain the stronger scattering but it cannot be responsible for the arc-shaped scattering. The arcs indicate that there is a strong scattering within the plane of the guiding structure with subsequent out-coupling of the scattered waves. In other words, if a given Fourier component of the surface roughness happens to provide a resonant coupling between the modes of a planar structure, the scattering is strong. Another Fourier component with close period and orientation, but beyond the resonant condition, may provide only a negligibly small contribution to scattering because there is no suitable guided mode final state for the scattering wave. There could be also the Fourier components that provide scattering to waves propagating in free space. This scattering must be much weaker compared to the scattering to guided modes in order to achieve the arc-shaped scattering picture.

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In other words, intensity of scattering on surface grating strongly depends on the final state of the scattered wave, namely, whether the scattered wave is a guided mode or wave in the three-dimensional space. There is a clear analogy for this phenomenon in quantum mechanics. The gold Fermi rule for electron transitions in a periodical field is probably the first known formulation of the relationship between the probability of the process and the density of states in the final state. According to this rule, the probability of electron transition is proportional to the density of states in the final state. Consequently, in a random field characterized by wide spectrum of field oscillations, only certain spectral components of the perturbation field affect the quantum system. These components provide transition to a localized energy level with delta-like density of states. Similar rules are applied to many different processes involving different kinds of waves. For example, intensity of spontaneous emission is proportional to photon density of states in the final state and hence becomes controlled in microcavities and photonic bandgap structures. Scattering of phonons in superlattices is also controlled by a similar mechanism.

In the case of light scattering of guided modes, the surface roughness plays the role of the perturbation that serves as a coupling between the incident and the scattered wave. One can treat a rough surface as a superposition of the Fourier components of the surface profile, that is, as a set of diffraction grating with all possible periods and orientations. The gratings with very similar periods and orientation can nevertheless have very different contribution to the scattering of the guided mode depending on whether or not the final state is another guided mode.

The enhanced scattering is easily observed and, undoubtedly, has been noticed by researchers working with dielectric waveguides. The arcs around the reflected beam appear in both prism and grating coupler schemes. They often used as a clear indicator of a waveguide excitation. What we emphasize in this paper is that the shape of the scattering pattern provides a proof of guided mode to guided mode scattering being much stronger than scattering out of the guiding film.

The non-resonant and resonant scattering cases are illustrated by wave-vector diagrams in Fig. 1. The direction of scattered wave is determined by the projection of incident wave-vector on the plane of the waveguide and the roughness wavevector. When no guided mode involved (Fig. 1a), it simply gives

$$\vec{k}_s = \vec{k}_i + \vec{k}_r \tag{1}$$

We refer to this case as direct scattering on the surface roughness. It is certainly non-resonant process and there is no reason to expect that small variations of the direction of magnitude of $\vec{k}_r$ could significantly affect the intensity of scattering.

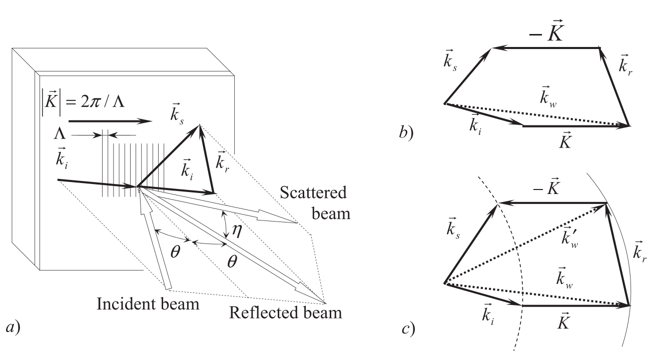

Fig. 1. (a) Wavevectors representation that corresponds to waveguide mode excitation in planar waveguide with imperfections; (b) wavevectors representation for the mode coupling by the diffractive gratings; (c) wavevectors representation for the evolution of the arc-shape scattered light that associates the excitation of guided mode.

In the presence of a coupling grating, a waveguide mode with wavevector $\vec{k}_w = \vec{w} \cdot k_0 n^*$ is excited in the first order of diffraction at the coupling grating with wavevector $\vec{K}$ when the phase matching condition is satisfied.

The excitation of guided modes condition is as follows:

$$\vec{K} + \vec{p} \cdot k_0 \sin(\theta) = \vec{w} \cdot n^* k_0, \tag{2}$$

where $|\vec{K}| = 2\pi/\Lambda$ is the grating's wavevector, Λ is the grating's period, $k_0 = 2\pi/\lambda$ is the vacuum wavevector of light, λ is the wavelength, θ is the resonant angle measured from the normal to the sample, $\vec{p}$ is the unit vector along the projection of the incident wavevector on the plane of the sample, $\vec{w}$ is the unit wavevector along the guided mode propagation direction, and n^* is the modal index.

The wave scattered by the surface roughness component with wave-vector $\vec{k}_r$ becomes observable due to the negative first order of diffraction (Fig. 1b), which eventually results in the same relation between the wave-vectors of the incident and the scattered waves as in the case of the direct scattering as in Eq. (1). Although this process involves excitation of the waveguide mode, we refer to it as non-resonant since the final state of scattering by $\vec{k}_r$ is not a waveguide mode.

Finally, there could be a situation, when $\vec{k}_w + \vec{k}_r = \vec{k}'_w$ which is the wavevector of another waveguide mode, propagating at different direction. The scattering direction (Fig. 1c) is still determined by Eq. (1), but the intensity is expected to be much stronger in accordance with the above consideration. Note, that $|\vec{k}'_w| = k_0 n^*$ means that the ends of vectors $\vec{k}'_w$ are placed along the arc with radius $k_0 n^*$, which eventually is transferred into another arc in the directions of scattered waves $\vec{k'}_s = \vec{k'}_w - \vec{k}_g$ shown as a dashed line in Fig. 1c. Note also, that non-resonant scattering and the resonant one have only one significant difference: the surface roughness component $\vec{k}_r$ in the non-resonant case couples three-dimensional waves in the free space ($\vec{k}_i$ and $\vec{k}_s$), while in the resonant case it couples two-dimensional guided modes ($\vec{k}_w$ and $\vec{k}'_w$). The arc-shaped scattering confirms that the resonant mechanism is much stronger despite the fact that it involves diffraction on the coupling grating, diffraction on the surface roughness, and diffraction on the coupling grating while the non-resonant scattering directly couples the incident and the scattered waves. This is rather important observation: the same kind of surface roughness may cause either negligible scattering or very strong scattering depending on whether and how the guided modes are involved into the scattering process.

The above qualitative explanation can be also supported by a simple numerical consideration. In the non-resonant state, the electric field strength of scattered wave is proportional to $k_0\sigma_r$, where σ_r is the amplitude of a Fourier component of surface roughness with wave-vector $\vec{k}_r$. Efficiency of the non-resonant scattering η_{NR} becomes proportional to the second order of surface roughness amplitude:

$$\eta_{NR} \propto (k_0\sigma_r)^2 \tag{3}$$

In general, light scattering by surface roughness treated as Fraunhoffer diffraction is one of optical approaches for the evaluation of surface roughness. Exact formula would contain few other factors in order to account for the polarization of the waves, angles of incidence and scattering, indexes of refraction and thickness of the layers composing the structure. Those details are beyond the scope of this paper, so we keep only the leading term relating the efficiency of scattering to the roughness amplitude. In the case of the resonant scattering, when both incident and scattered waves are the guided modes, the Fourier component of the surface roughness provides efficient Bragg coupling between them. The coupling coefficient κ is proportional to $k_0\sigma_r/h^*$ where h^* is the effective thickness of the waveguide, typically of the order of λ or, maybe,