Narrow-band filtering with whispering modes in gratings made of fibers

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Abstract: We present a numerical study of whispering modes in gratings made of fibers. Due to the strong localization of the modes inside each fiber, it is possible to obtain narrow-band filters with very broad angular tolerance.

OCIS codes: (230.7408) Wavelength filtering devices; (050.0050) Diffraction and gratings; (060.0060) Fiber optics and optical communications; (260.5740) Resonance.

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1. Introduction

Grating anomalies attract attention since the famous observation by R. Wood that grating efficiency can vary several orders of magnitude within a very short spectral interval [1]. While very boring for grating manufacturers, these anomalies, due to excitation of eigenmodes in the grating structure, have found practical application in detection and filtering [2-5]. The resonances can be due to surface waves (surface plasmons) along dielectric-metallic interfaces [6], guided modes of dielectric waveguides [5], cavity [7] or Fabry-Perot resonances [8].

The resonant anomalies can be characterized by sharp maxima or minima whose width depends on the resonance finesse and losses. For lossless dielectric waveguides with shallow corrugation, the width of the peak can be reduced to less than several angstroms. However, excitation of guided modes, which leads to very narrow spectral lines, is characterized by strong sensitivity with respect to the angle of incidence and thus requiring very tight tolerances with respect to the collimation of the light beams [9]. Several approaches are proposed to decrease the angular constraints of such devices, keeping the spectral lines as narrow as possible. The first approach is to flatten the mode dispersion curve by using the Bragg interaction between counter-propagating modes [10]. A second approach is to juxtapose the flatten dispersion curves of two modes, which is possible with deep gratings [11]. The third approach is based on the use of cavity resonances, which are generally characterized by strong spectral variation and much weaker angular dependence. This difference can be understood by taking into account that resonances localized in the direct space have larger support in the inverse space. The problem is that the creation of cavity resonances with large finesse requires use of metallic walls, because the only-dielectric grating provides strong coupling between the consecutive periods and thus reducing the finesse. Unfortunately, in the visible, metals have losses, strongly enhanced when resonances are excited, which significantly reduces the application performances. On the other hand, since Lord Rayleigh [12], it is known that even purely dielectric systems can support well-localized modes, called whispering (gallery) modes, because they were discovered in acoustics. These modes can exist in optical fibers and in dielectric spheres, provided the optical dimensions are large enough. They are characterized by strong field maxima localized inside but close to the surface of the object and can be considered from a geometrical point of view as due to total reflection of the beam propagating inside the fiber or the sphere.

There are many papers devoted to whispering modes (WsM) in optical fibers, although much less than in dielectric spheres. Initially, the interest was motivated by bending and coupling losses in fibers [13-20]. More recently, the use of WsM for guiding of light has been proposed [21-23]. Although the WsM are lossy (radiative), they can guide light along a long chain of aligned fibers [24], because the losses are small, as we discuss later. The aim of this paper is to study the possibility of using the whispering modes in periodically arranged optical fibers for optical filtering, characterized by narrow spectral lines and large angular tolerances. All studies available in the literature concern WsM having a non-zero constant of propagation along the fiber axis, a natural choice determined by the common use of fibers to carry light. By contrast, most filtering devices are designed to work at normal incidence, i.e., in direction perpendicular to the fiber axis, a configuration in which the longitudinal component of the propagation constant vanishes. In the second section of the paper, we will show that gratings

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made of fibers illuminated under normal incidence can present narrow-band and angularly tolerant resonances. The third section will be devoted to show that these radiative properties are actually related to the excitation of whispering modes.

2. Narrow-band and angularly tolerant resonances in gratings made of fibers

To simplify the understanding of the phenomena, we use step-profile fibers without cladding, suspended in air. There are several complications that should appear and must be solved for any practical application. First, the whispering modes are very sensitive to fiber dimensions, thus identical fibers must be used. Second, suspending fibers in air is technically almost impossible, thus a dielectric matrix has to be used. Third, in order to maintain the required distance between the fibers during their assembly in the grating, there are two possibilities: either to use fibers with low-index cover, with total diameter equal to the grating period, or to use some self-assembling technique, such as putting the fibers on a Si surface with etched equidistant grooves. However, such technical analysis lies outside the scopes of this paper. Figure 1 represents schematically the rod grating under study. The working polarization is TE, electric field vector parallel to the fibers. All along the paper, the plane of incidence is perpendicular to the fibers axis (e.g. the *(Oxy)* plane). The wavelength is close to 1.55 µm, the fibers are made of Si with refractive index n_2 = 3.45, and suspended in air (refractive index n_1 = 1). The period d is equal to 1.45 µm. Consequently, near normal incidence, the only propagating orders are the reflected and transmitted zeroth orders.

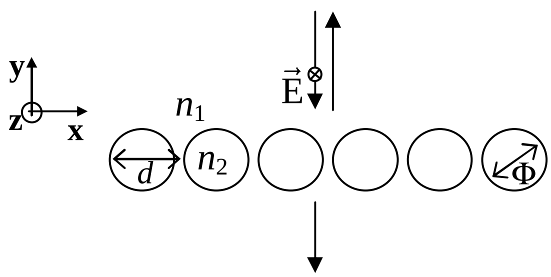

Fig. 1. Rod grating under study.

As can be expected from general theoretical considerations [5], in the vicinity of resonance excitation, one can expect the reflectivity to vary from 0 to 100%. Figure 2 presents the behavior of the reflectivity as a function of the fiber diameter Φ.

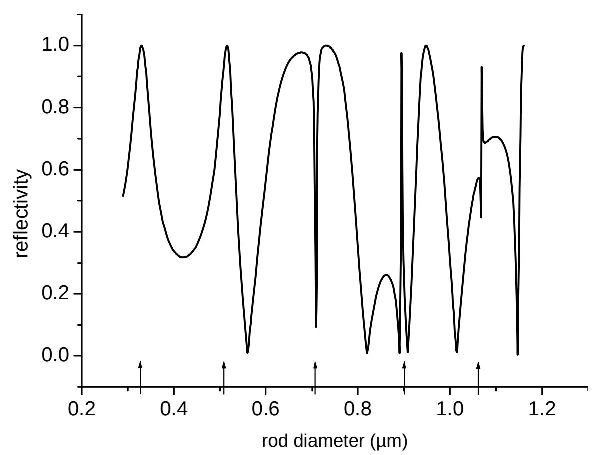

Fig. 2. Reflectivity of the rod grating of Fig. 1 versus the rod diameter (in µm). Period d = 1.45 µm, wavelength λ = 1.55 µm, TE polarization, normal incidence, rod refractive index equals to 3.45.

#87581 - $15.00 USD Received 17 Sep 2007; revised 6 Nov 2007; accepted 6 Nov 2007; published 12 Nov 2007

The calculations are performed thanks to the Integral Method [25]. One can observe multiple anomalies, which are wider for smaller diameters and become very narrow when the fiber diameter becomes large. This can be expected, because the WsM become more localized for larger rods, a fact that is illustrated further on. Stronger localization is also expected to lead to larger spectral finesse. Indeed, localization means that the field of the mode is confined into the cylinders, which is related to weak losses in the superstrate. Figure 3 shows that the spectral dependence of the different anomalies indicated with arrows in Fig. 2 is significantly sharpened with the increase of rod diameter Φ.

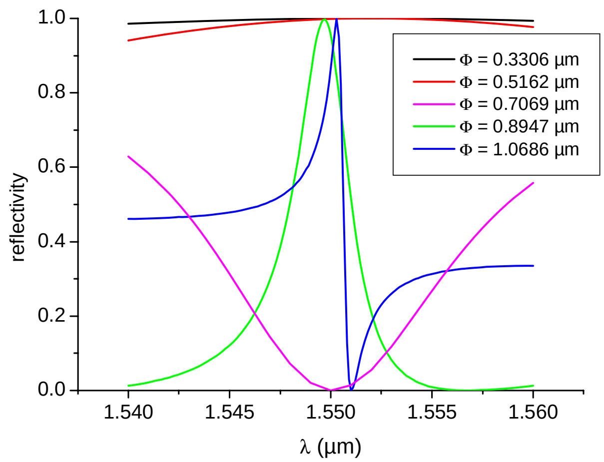

Fig. 3. Spectral dependence of the reflectivity of the rod grating presented in Fig. 1. Period d = 1.45 µm. The rod diameters Φ correspond to the anomalies indicated with arrows in Fig. 2.

Let us thoroughly study the system composed of fibers with diameter 0.8947 µm, chosen among the others as having a spectral response most suitable for narrow-band reflection filtering. We plot on Fig. 4 the angular dependence of the reflectivity. It presents a flat top resonance expanding over a wide angular range. The reflectivity decreases quickly for angles greater than 4° because the first order of the grating becomes propagative above 4°.

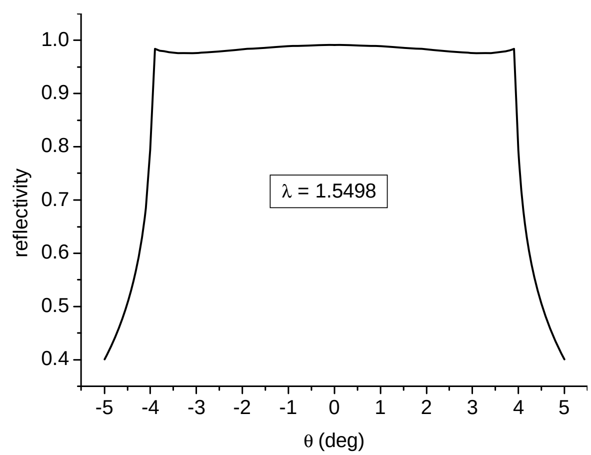

Fig. 4. Angular dependence of the reflectivity of the rod grating with period 1.45 µm, rod diameter 0.8947 µm.

An angular tolerant resonance is especially interesting in practical filtering applications for two reasons. First, experimental incident beams have non-zero divergence, which may cause a loss of filtering efficiency for low angular tolerant resonances [26]. Second, an angular tolerant filter will be efficient even for focused incident beam and devices having small dimensions. As an example, the grating composed of 0.8947 µm diameter fibers will keep its efficiency for incident beams with convergence angle up to 8°, which corresponds to a Gaussian beam with waist diameter of about 13 µm (for a wavelength of 1.55 µm). We plot on Fig. 5 (solid curve) the reflectivity versus the incident wavelength for a finite-size grating of 30 µm length, illuminated by a Gaussian beam (invariant along the z-axes) with 20 µm waist. The calculations were performed using the Scattering Matrix Method [27]. The curve is almost the same as that obtained for the infinite grating illuminated by a plane wave under normal incidence (dashed curve), except for the peak observed around 1.544 µm. This extra resonance is caused by the non-normal incident plane waves that compose the Gaussian beam and which can couple modes having anti-symmetric fields with respect to the normal to the grating, contrary to the normally incident plane wave. For confirmation, the extra resonance also appears when the infinite grating is illuminated by a plane wave with an angle of incidence of 2° with respect to the z-axes in the *(Oxy)* plane.

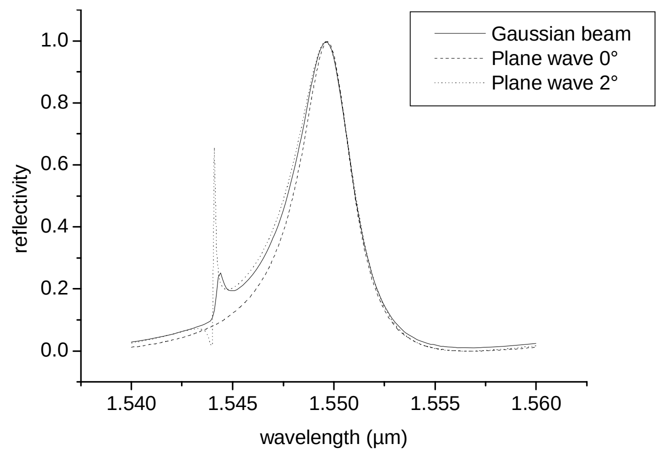

Fig. 5. Spectral dependence of the reflectivity of the finite rod grating illuminated by a Gaussian beam (solid curve), infinite grating illuminated by a plane wave under normal incidence (dashed curve) and under an incidence of 2° (dotted curve) (period 1.45 µm, rod diameter 0.8947µm).

3. Physical insight into the origin of the resonance properties

In order to find the physical origin of these anomalies, we plot on Fig. 6 the modulus of the electric field inside the structure at the resonance wavelength. One can observe that the field is particularly localized into the fibers.

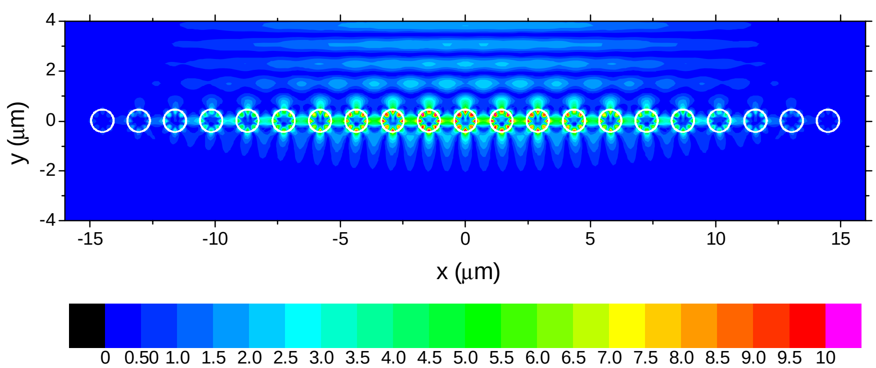

Fig. 6. Modulus of the electric field for the finite rod grating (period 1.45 µm, rod diameter 0.8947 µm) illuminated by a Gaussian beam with 20 µm diameter at waist.

#87581 - $15.00 USD Received 17 Sep 2007; revised 6 Nov 2007; accepted 6 Nov 2007; published 12 Nov 2007

The natural hypothesis that imposes is that the mode excited in the 30 µm length grating is composed of a single mode inside each fiber, slightly modified by the coupling occurring between the modes of the neighboring fibers. Therefore, we investigate at first a single fiber under the same illuminating conditions. For each of the diameters pointed by arrows in Fig. 2, using the method described in [28], we have found the complex pole λ_p of the scattering matrix for a single fiber around 1.55 µm. The real part of the pole represents the resonance wavelength, while the imaginary part is related to the spectral width of the resonance. The map of the electric field in the fiber when it is illuminated by a plane wave at the resonance wavelength is represented in Fig. 7. As expected from the theory of WsM, the localization of the mode field decreases with the rod diameter. This is confirmed by the value of the imaginary part of the pole, which increases when the rod diameter decreases.

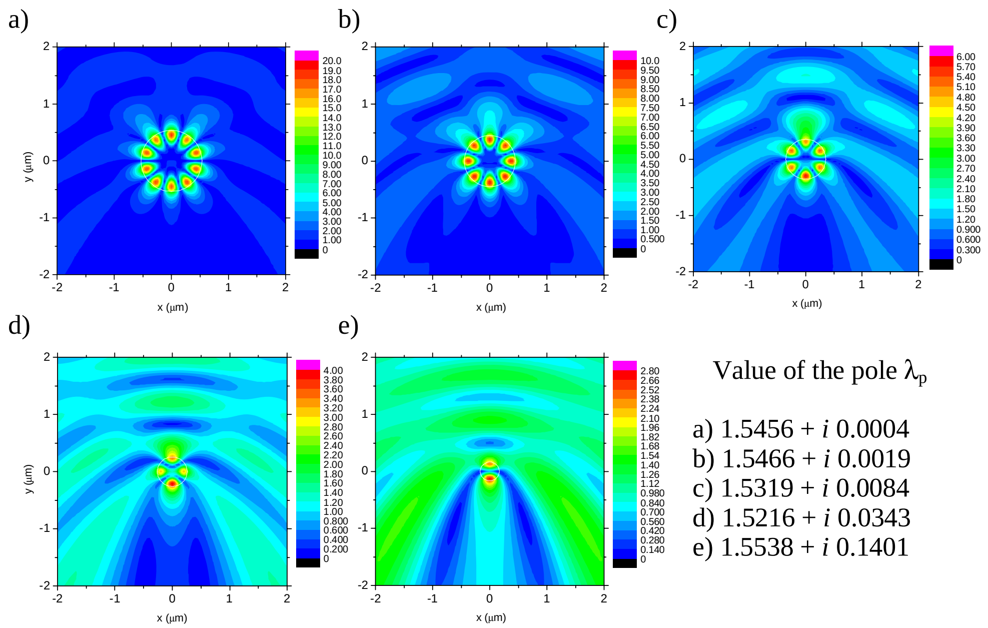

Fig. 7. Modulus of the electric field at the resonance wavelength for a single fiber, with diameter (a) 1.0686 µm, (b) 0.8947 µm, (c) 0.7069 µm, (d) 0.5162 µm, (e) 0.3306 µm. The modulus of the incident plane wave is normalized to 1.

The natural question that arises is to know to what extend the WsM resonances remain localized when the fibers are assembled into a grating, as there is an inevitable coupling between the modes in the adjacent fibers through the air gap, which decreases sharply with the increase of the diameter. Let us consider a system of two fibers, with diameter 0.8947 µm. The coupling leads to a splitting of otherwise degenerate mode of the single fiber into four modes, because the cylindrical rotation symmetry is broken into a reflection symmetry with respect to the x- and y-axes (see Fig. 1), thus permitting modes that are symmetrical or anti-symmetrical with respect to these axes. The four poles (in the spectral range of interest) of the scattering matrix of the structure are reported in Tab. 1. They are actually distributed in the neighboring of the pole of one single fiber ($1.5466 + i\ 1.9\ 10^{-3}$), and are characterized by a smaller or larger imaginary part. Hence, the coupling leads to both stronger and weaker localized modes. Note that the mode which is symmetrical with respect to x- and y-axes has an imaginary part twice as large as the other modes. This can be explained by the fact that the field of this mode has the same symmetry as that of the plane waves radiated along the x- and y-axes, i.e., this mode is more easily radiated along both axes (including their positive and negative directions) than the other modes.

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Tab.1. Poles of the structure composed of two fibers with diameter 0.8947 µm, separated with a distance of 1.45 µm.

Pole	Symmetry / Ox	Symmetry /Oy
$1.5433 + i\,1.4171\ 10^{-3}$	Symmetrical	Anti-symmetrical
$1.5450 + i\,1.5605\ 10^{-3}$	Anti-symmetrical	Anti-symmetrical
$1.5483 + i\,1.1720\ 10^{-3}$	Anti-symmetrical	Symmetrical
$1.5487 + i\,2.7626\ 10^{-3}$	Symmetrical	Symmetrical

Last, it is expected that the coupling between the modes of the fibers depends on the distance between the fibers. Hence it may be possible to tune the spectral bandwidth of the resonance by changing the distance between the fibers. We show in Fig. 8 that a twice shorter (2 nm) bandwidth can be obtained with the same 0.8947 µm diameter fibers separated by a longer grating period of 1.49 µm. The angular tolerance of the resonance is limited, as for the grating with period 1.45 µm, by the first order of the grating which becomes propagative for angles greater than 2.3°.

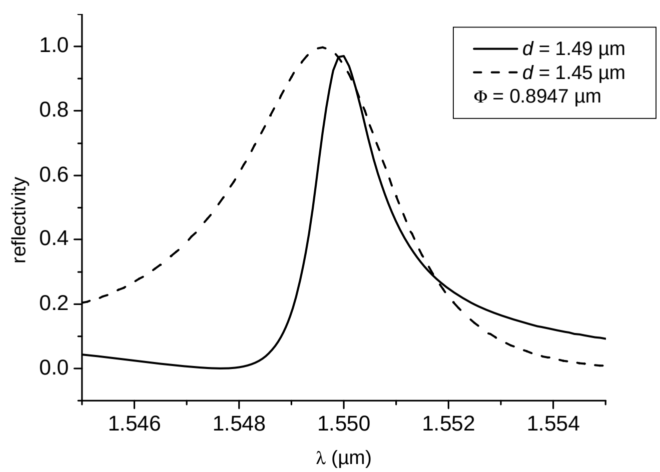

Fig. 8. Spectral dependence of the reflectivity of the rod grating presented in Fig. 1. Period $d = 1.49$ µm (solid curve) and $d = 1.45$ µm (dashed curve), rod diameter $\Phi = 0.8947$ µm, illuminated by a plane wave in normal incidence.

4. Conclusion

To conclude, we have shown that spectral filters with narrow bandwidths and broad angular tolerances can be obtained by using the excitation of whispering modes in gratings made of fibers. The spectral width over wavelength ratio can be as weak as 10^{-3}, with an angular width as large as 5°, only limited by the fact that the first order of the grating becomes propagative. The spectral bandwidth depends on the coupling between the modes of each fiber, which is related to the distance between two neighboring fibers. This result allows us to conjecture that it will be possible to obtain ultra-narrow bandwidths (smaller than 1nm) with broad angular tolerance. However, the coupling mechanisms are complex and further studies may be necessary to be able to design ultra-narrow bandwidth filters.

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