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# Multifrequency spatial filtering: A general property of two-dimensional photonic crystals

A.E. Serebryannikov [a,b,*], E. Colak [c], A. Petrov [d,e], P.V. Usik [f], E. Ozbay [b]

[a] *Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
[b] *Nanotechnology Research Center – NANOTAM, Bilkent University, 06800 Ankara, Turkey*
[c] *Department of Electrical and Electronics Engineering, Ankara University, Golbasi, 06830 Ankara, Turkey*
[d] *Institute of Optical and Electronic Materials, Hamburg University of Technology, 21073 Hamburg, Germany*
[e] *ITMO University, 49 Kronverskii Ave., 197101 St. Petersburg, Russia*
[f] *Institute of Radio Astronomy, National Academy of Sciences of Ukraine, 61002 Kharkiv, Ukraine*

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## Abstract

Spatial filtering, an analog of frequency-domain filtering that can be obtained in the incidence angle domain at a fixed frequency is studied in the transmission mode for slabs of two-dimensional rod-type photonic crystals. In the present paper, the emphasis is put on the demonstration of the possibility to obtain various regimes of spatial filtering, i.e., band-stop, band-pass, and low-pass filtering in different frequency ranges in one simple configuration. The operation is based on the use of several Floquet–Bloch modes with appropriate dispersion properties, so that such one or two co-existing mode(s) contribute to the forming of a proper filter characteristic within each specific frequency range. It is shown that high-efficiency transmission and steep switching between pass and stop bands can be obtained in the angle domain for wide ranges of variation of the problem parameters. In particular, by varying the rod-diameter-to-lattice-constant ratio, one attains lots of freedom in the engineering of spatial filters with desired transmission characteristics.

*Keywords:* Spatial filtering; Photonic crystal; Floquet–Bloch mode; Transmission; Fabry–Perot resonance

## 1. Introduction

Spatial (angular) filters are important components required in information processing and image enhancement for various frequency ranges. They operate in the incidence angle domain at a fixed frequency, $f$, and thus represent analogs of the conventional frequency filters that operate at a fixed incidence angle, $\theta$. Spatial filters are also considered from the spatial-frequency filtering perspective [1]. For example, such filters were employed in the analysis of the spatial spectrum, enhancement of the antenna directivity, radar data processing, aerial imaging, and sorting the incoming radiation according to the source location. The known theoretical and experimental performances of the spatial filters include those based on anisotropic (anti-cutoff) media [2], multilayer stacks combined with a prism [3], resonant grating systems [4], metallic grids over a ground plane [5], interference patterns [1], and axisymmetric microstructures [6]. Various photonic crystal (PhC)

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[*] Corresponding author.
*E-mail address:* aeserebr@gmail.com (A.E. Serebryannikov).

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structures that enable efficient spatial filtering should be mentioned, including those based on two-dimensional regular (defect-free) PhCs and one- and two-dimensional chirped PhCs [7–11]. The co-existing spatial and frequency filtering has also been studied in connection with the control of laser radiation with the aid of the resonant grating based filters [12]. The state-of-the-art of spatial filtering has been reviewed in [13].

The known mechanisms of spatial filtering differ in that they use [2,7–9,11] or do not use [1,4] the peculiar dispersion features. The former may give more freedom in design, because the required features can appear in wide ranges of frequency and/or angle of incidence. For instance, low-pass spatial filtering can be obtained by using volumetric structures with isotropic-type dispersion, which corresponds to the refractive index values within the range of $0 < n < 1$ [14]. In turn, high-pass and band-pass filtering require structures with anisotropic-type dispersion. Generally, these types of spatial filtering can be attained by using anti-cutoff media [2], which are also associated with hyperbolic metamaterials [15] and PhCs with the dispersion features that enable blocking transmission in the vicinity of zero of tangential wavenumber [7–9]. The problem can appear when a nearly perfect transmission within the entire wide angle-domain pass band is required [16,17]. High-pass/dual band-pass spatial filtering that fulfills this requirement has been demonstrated in the transmission mode for a slab of the two-dimensional dielectric PhC [7]. For operation in the reflection mode, high-/band-pass spatial filters have recently been suggested, which are based on two-dimensional PhCs and single-layer rod arrays over a metallic reflector [18]. Note that the reflection mode high-/band-pass spatial filters require the redistribution of the incident-wave energy in favor of higher diffraction orders, i.e., this mode is connected with the blazing regime [19]. On the contrary, the transmission mode does not require the contribution of higher orders, although blazing, if appears, can lead to some advances in functionality. Regardless of the possible contribution of higher orders, the richness of dispersion features remains the main argument in favor of using two-dimensional PhCs.

In this paper, we demonstrate that a rich variety of the types of spatial filtering, e.g., low-pass, high-/band-pass and bandstop filtering can be realized in one simple configuration that represents a finite-thickness slab of a two-dimensional PhC composed of circular dielectric rods. The crucial key knobs of the initial design stage that is based on the dispersion analysis include the following: (i) engineering single or multiple Floquet–Bloch waves by having bands with monotonous dispersion which are separated well from each other, bands with nonmonotonous dispersion, or co-existing bands; (ii) engineering the relative position of the modes within the first Brillouin Zone (BZ) with respect to the equifrequency dispersion contours (EFC) in air (for instance, isotropic-type EFCs of PhC narrower than in air favor low-pass spatial filtering; anisotropic-type EFCs would favor high-/band-pass spatial filtering); and (iii) engineering the shape of EFCs (e.g., square shape of EFCs is expected to be preferable to keep nearly the same transmission efficiency within the entire band). These points are illuminated by the analysis of the possible combinations of EFCs in air and PhC and related coupling scenarios. Then, we show by using the simulated transmission results that solely a proper parameter adjustment can enable different types of spatial filtering in the neighboring frequency ranges. To realize a desired response in the angle domain at a fixed frequency, either a sole Floquet–Bloch mode or two such modes are employed. The sharp filter properties are obtained due to the contributions from several effects, such as the shape of the EFCs, Fabry–Perot type interferences, and the excitation of higher diffraction orders. The transmission results have been obtained by using the coupled-integral-equation technique, a flexible iterative technique which enables acceleration in convergence by applying preconditioning [20].

## 2. Dispersion based analysis

The basis of operation of spatial filters is connected with the distribution of the Floquet–Bloch modes in the *entire* wavevector space (not just in the first BZ). It is well known that electromagnetic waves follow in PhCs the Floquet–Bloch theorem as electrons in a crystal. Therefore, the distribution of the modes in the wavevector space can be reconstructed from the one in the first BZ according to a *repeated zone scheme*, by following the symmetry of the lattice just like in the electronic case. This approach can simplify both analysis and design significantly. It is noteworthy that an extensive analysis of refraction in PhCs, by taking into account the mode distribution in the entire wavevector space, was first done by Foteinopoulou and Soukoulis [21]. For the purposes of spatial filtering by using PhCs, the results presented in [21] are very important since they illustrate the possible behavior (shape and locations) of the EFCs for PhC in the entire wavevector space, whilst the sign of refraction and handedness are not so important, in the contrast to what might be important for other applications. The same remains true for other previous studies of PhCs, e.g., see [22,23]. Comparing to the study of refraction in