Bound states in the continuum in symmetric double-sided grating metamaterials

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***Abstract*— We study quasi-bound states in the continuum with diverging resonance lifetime and vanishing resonant linewidth in a novel double-sided grating metamaterial. With rigorous computations, we corroborate that specific physical conditions are required to obtain the diverging resonance quality factor.**

Keywords—bound states in the continuum, guided-mode resonance, metamaterials, resonant periodic films, quality factor

I. Introduction

Optical bound states in the continuum (BICs) can be considered as trapped modes with an infinite lifetime above the light line in the dispersion diagram of a periodic structure. These confined modes with extremely high quality factors (Qs) amplify light-matter interactions potentially enabling low-threshold lasers. Among different types of BICs, a true BIC is a completely non-radiative mode with resonance linewidth of exact zero ($\Delta\lambda=0$); however, other types of BICs may be quasi-BICs which their resonant linewidth approaching zero ($\Delta\lambda\rightarrow0$) but not identically zero. These nearly-zero resonance linewidths possess quasi-embedded eigenvalues which cause coupling to radiated waves [1, 2]. The resultant narrow-line guided-mode resonance (GMR) occurring in subwavelength periodic structures [3] thus has a finite lifetime due to the coupling of the resonant mode to a free space radiated wave. One can manipulate the spectral response and resonance linewidth of the GMR device by changing the physical parameters of the subwavelength structure for desired applications such as polarizers, biochemical sensors, and optical filters [3, 4].

Although there exists extensive literature on single-sided grating resonance devices that can be easily fabricated on different substrates, double-sided resonance designs, which can exhibit substantial innovation potential in the field of nanophotonics, have not been adequately investigated. In traditional single grating devices, thin-film deposition methods of different materials are employed to obtain desired thin films with different refractive indices. For double-sided gratings, based on the thickness limitation of the homogeneous layer, we need to fabricate a membrane-type device. We already proposed and fabricated double-sided grating membrane-type structures via nanoimprint lithography (NIL) [5]. Avrutsky and his colleagues showed that in a waveguide structure with two corrugated boundaries, unidirectional output radiation is achievable [6]. Later, Kasraian derived four coupled-mode equations to describe the characteristic of the second-order Bragg interaction for TE modes of double-sided grating waveguides [7]; these works are relevant here [6, 7].

Here, we study quasi-BICs in double-sided grating membrane metamaterials. Numerical simulations establish spectral-parametric regions with vanishing resonant linewidths centered on specific values of the top/bottom grating depth ratio and the homogeneous layer thickness of the double-sided design.

II. BICs in Double-Sided Metamaterials

A schematic of a double-sided grating metamaterial surrounded by a cover and a substrate with refractive indices of n_1 and n_3 is depicted in Fig. 1. The value of Δ shows the lateral displacement of the two gratings on top and bottom sides of the homogeneous layer. For designs with $\Delta=0$ or $\Delta=\Lambda/2$, the symmetry of the structure is preserved.

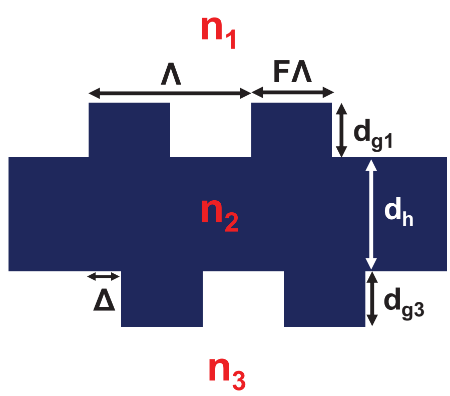

Fig. 1. Schematic of double-sided grating GMR metamaterial with lateral shift of Δ between top and bottom gratings.

Figure 2 shows computed transmission maps of wavelength versus homogeneous layer thickness (d_h) for different structures. The simulation is performed using the rigorous coupled-wave analysis (RCWA) method. Here, we consider the TE polarization state which is defined as input and resonant electric-field vector parallel to the grating lines (perpendicular to the grating vector). Figure 2(a) is related to the single-sided structure and Figs. 2(b)-(d) shows the transmission map of a double-sided structure with different lateral displacements. It is

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shown that for symmetric double-sided structures in Figs. 2(b) and 2(c), there exist regions with vanishing resonant linewidths appearing between two broadband areas. This behavior is completely different from the single-sided design. Therefore, it is shown that in symmetric dual gratings, as the thickness of the homogeneous layer approaches specific values, quasi-BICs emerge as the resonance linewidth asymptotically approaches zero. Moreover, it is shown in Fig. 2(d) that the quasi-BIC disappears in asymmetric double-sided designs.

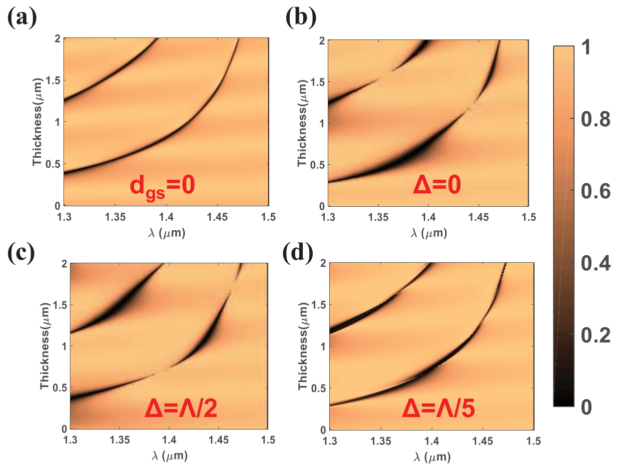

Fig. 2. Zero-order transmission map based on changing the thickness of the homogeneous layer with refractive index of n_2=1.5. (a) Traditional single-grating design. Symmetric double-sided metamaterial with lateral displacement of (b) Δ=0, and (c) Δ=Λ/2. (d) Asymmetric double-sided design with Δ=Λ/5. Physical parameters for devices are Λ=1 μm, d_{g1}=0.3 μm, d_{g3}=0.3 μm, F=0.5, and $n_1 = n_3 = 1$.

Based on the Avrutsky model [6], to suppress the radiation towards the cover, the following conditions prevail:

$$\frac{d_{g2}}{d_{g1}} = \frac{E_1(n_2^2 - n_1^2)}{E_2(n_2^2 - n_3^2)} \qquad (1)$$

$$kn_2 h = m\pi \qquad (2)$$

Here, m is an integer, k is the wave number, E_1 and E_2 represent the mode field amplitudes on the boundaries, and n_1, n_2, and n_3 are the refractive indices of the cover, film, and substrate, respectively. Substituting E_1 and E_2 for a classic slab waveguide from [8], we find the conditions for maximum transmission towards the substrate in simpler terms as

$$\frac{d_{g2}}{d_{g1}} = \sqrt{\frac{n_2^2 - n_1^2}{n_2^2 - n_3^2}} \qquad (3)$$

$$h_{BIC} = m\frac{\lambda_{res}}{2} \times \frac{1}{n_2} \qquad (4)$$

In 1994, Kasraian derived four canonical equations related to the second-order double-grating waveguide design. His derivation was based on including a non-vanishing second-harmonic term in the grating profile. He calculated the conditions at which radiation power to the cover and substrate vanishes for applications in frequency selective filters and output couplers. The resulting equations are identical to Eqs. (3) and (4) which are based on the Avrutsky formulation.

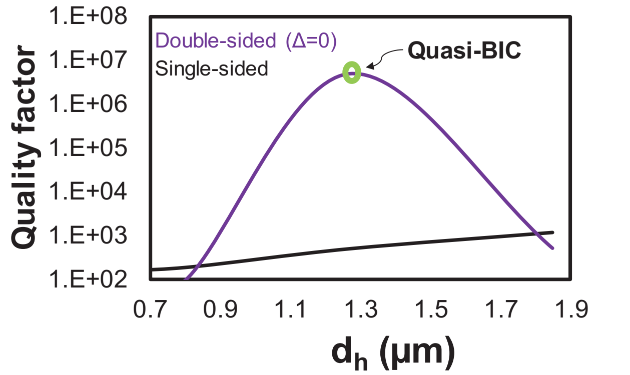

Fig. 3. Quality factor of single-sided and symmetric double-sided metamaterials.

Figure 3 shows the calculated quality factor for single-sided and double-sided grating structures. We can see that the ultra-high quality factor resonance (quasi-BIC) occurs for symmetric dual-grating structure when the conditions of the Eqs. (3) and (4) are satisfied. It is worth noting that our membrane is surrounded by air with refractive index of n=1.

In summary, optical BICs in dual-grating metamaterials are reported. For these designs, resonance properties contrasting strongly with those of single-sided resonance gratings are shown under variation of the thickness of the homogeneous layer. The highest Q occurs at specific physical parameters of the double-sided device satisfying grating-depth ratio and homogeneous layer thickness requirements but with regions of high Q persisting around that point for considerable expanses.

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