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Open Optical Cavities based on Metasurfaces

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Abstract
We generalize the concept of open optical cavity using one or more reflective metasurfaces instead of two curved mirrors. We provide a simple mathematical framework to describe it in the framework of Maxwell's equations and examples of applications to lasers and quantum emitters.

Key terms
Metasurface, Optical cavity

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1. Introduction

Metasurfaces have been considered as components for optical cavities in a few recent works [1, 2, 3, 4, 5, 6, 7]. In [2] we proposed the use of a reflective metasurface to create optical feedback towards a red laser diode, obtaining a tunable wavelength laser with arbitrary beam shaping. In [3] the metasurface is actually the gain medium in a laser operating at THz wavelengths. In [4, 5] metasurfaces operating in transmission in a laser cavity generate modes with orbital angular momentum, while in [6] the coupling of a single metasurface with emitters was investigated theoretically. We present here an outlook of new types of metasurface cavities and a general theoretical framework for the computation of the resonance modes in these metacavities.

2. Cavities based on metasurfaces

The results presented in [2] were obtained with a laser diode which had a high reflection (HR) coating on one facet and an anti-reflection (AR) coating on the other. This device cannot lase independently and requires an external cavity on the AR side to provide optical feedback. We demonstrated that this can be achieved with a metasurface fabricated on a reflective substrate which using a supercell architecture can retroreflect and focus the light directly on AR-coated facet. The chromatic aberration can be used to tune the wavelength simply by translating the metasurface. We also demonstrated that the output beam can be shaped independently using multifunctional supercells [2]. Nevertheless, many challenges remain unsolved and provide exciting research opportunities, such investigating applications to cavity electrodynamics and other tuning mechanisms.

For instance, electrical rather than translational wavelength control can be implemented using a spatial light modulator between the laser diode and the metasurface (Fig. 1A), which could be integrated directly in a beam steering metasurface [8, 9]. Another possible configuration is the creation of a supermode laser [10] using a metasurface, i.e. phase locking multiple solid state lasers and merging their output coherently in a single beam to achieve higher output powers (Fig. 1B). Generalized open optical cavities can be created by a reflective metasurface and a mirror or two reflective metasurfaces. They can be used in lasers using a rod shaped gain medium to control the modes geometry inside the laser, suppress unwanted modes and jointly control the polarization and shape of the output beam (Fig. 1C). Finally, these cavities can also be used for many other applications, including the control of wavelength, polarization and Purcell factor for quantum emitters (Figure 2), coupling multiple emitters, polariton chemistry [11] and to extend the already rich set of applications of metasurfaces for quantum photonics [12].

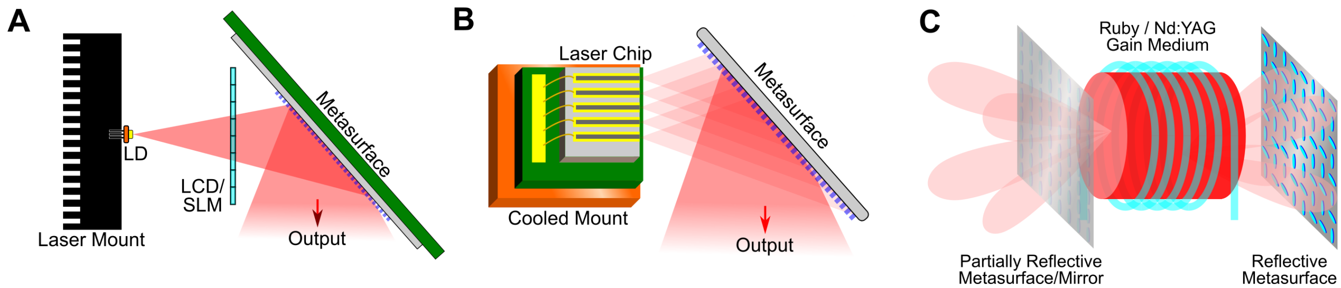

Figure 1: Laser systems based on metacavities. A) Electronic wavelength scanning. B) Supermode laser formed by a metasurface and an array of lasers. C) Metasurface laser for rod-shaped gain media.

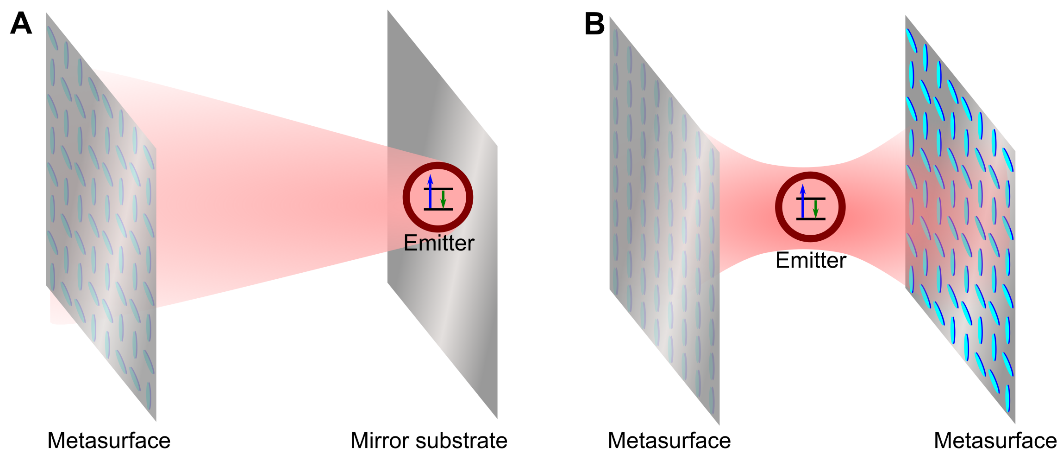

Figure 2: Metacavities for emitters. A) Metasurface + mirror. B) Double metasurface.

3. Theoretical framework

The task of identifying the resonant modes of the cavity for a two reflective metasurfaces system can be reduced to a simple eigenvalue problem. The EM fields can be represented as a vector ψ of complex numbers according to any selected basis at the central wavelength. For instance, we will use here the k-space of plane waves. The fields undergo a round trip including propagation from metasurface 1 to 2 (represented by operator P_{21}), reflection on the second metasurface (M_2), propagation back to the first metasurface (P_{12}) and the reflection on it (M_1). For empty space between metasurfaces, propagator P_{12} and P_{21} are unitary diagonal matrices in the plane wave basis. For metasurfaces 1 and 2, if they are local, $M_{1,2} = \mathscr{F} R_{1,2}(x,y) \mathscr{F}^{-1}$, where $\mathscr{F}$ is the 2D Fourier transform operator and $R_{1,2}(x,y)$ is the reflectivity profile of the metasurfaces. If the metasurfaces elements are not unpolarized, then a Jones matrix has to be used for $R_{1,2}(x,y)$.

The full round trip is then $M_1 P_{12} M_2 P_{21}$ and the resonant modes are invariant to the round trip, hence they are found solving the eigenvalue problem:

$$M_1 P_{12} M_2 P_{21} \psi = g \psi \quad (1)$$

In general, g is a complex number and all operators depend on the wavelength λ. Resonance occurs for λ such that the phase of g is zero or a multiple of 2π, while the absolute value of g is a measure of the cavity loss or gain. Therefore $g = 1$ for a stable lasing mode. For more complex configurations including transmitting elements, these can be added in the round trip term in equation 1 in a similar way. Thanks to this eigenvalue formulation, well known eigenvalues algorithms can be used for instance to suppress unwanted competing modes or to investigate topologically robust eigenmodes to minimize the effects of defects in the metasurface.

4. Conclusion

Metasurfaces allow a much greater flexibility compared to other optical elements handling complex laser modes or multiple emitters. In wavelength-tunable systems expliting the intrinsic chromatic aberrations of metasurfaces can replace multiple optical components and create a more compact design, shifting the complexity to the CAD file.

Important challenges are the precision of the fabrication to limit the scattering due to the disorder of the elements and the losses in the metal, which can be addressed respectively investigating the use of topologically protected modes and dielectric mirrors instead of metallic reflectors.

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