Sub-wavelength resonances in metal-dielectric-metal plasmonic structures

Shanhui Fan, H. Shin, M. Brongersma, G. Veronis, J. -T. Shen, P. B. Catrysse
Stanford University, Stanford, CA 94305 USA

Abstract – **Metal-dielectric-metal structures support propagating electromagnetic modes that are strongly confined in the dielectric region. These modes can be used to create omni-directional absorbers, sub-wavelength waveguides, negative refraction lens, and high-dielectric-constant meta-materials.**

I. INTRODUCTION

Here we consider some of the applications of sub-wavelength propagating modes in metal-dielectric-metal (MDM) structures. These structures consist of two metallic regions placed in close proximity to each other with a dielectric region in between. We show that the presence of such propagating modes can be used to create new meta-materials with dielectric constants that are frequency-independent, controlled only by geometry and can be arbitrarily large. Furthermore, in the optical wavelength range, with the metal region exhibiting plasmonic dispersion relation, the MDM structures can be used to support omnidirectional resonance, and to create sub-wavelength bound modes that propagate at high group velocities over substantial propagation distances.

II. OMNIDIRECTIONAL ABSORBERS

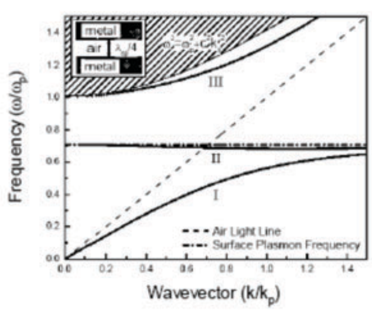

Fig. 1. The dispersion relation of a planar metal-dielectric-metal structur

Planar microcavity structures have been widely used to provide resonant enhancement of performance in opto-electroic devices such as light emitting diodes, modulators, and amplifiers. In all previous works, resonant enhancement at a given wavelength occurs only within a very narrow angular range. Such effect has limited the application of planar microcavity structures when a wide angular range of input and output is required.

Here we introduce a microcavity structure in which the resonant wavelength is largely independent of angle of incidence [1]. (We refer to such a resonance an omnidirectional resonance). The structure consists of a metal-dielectric-metal (MDM) configuration, and operates at the surface plasmon frequency of the metal-dielectric interface.

The operating principle of the omnidirectional resonance can be best understood by considering the dispersion relation for a MDM structure (Fig. 1a), in which both metal regions are semi-infinite. As a starting point, we use the lossless Drude model for the metal dielectric function:

$$-(-) = 1 - -_p^2 / -^2$$

where ω_p is the plasma frequency, and calculate the dispersion relation with transfer matrix formalism. The dispersion relation relates the frequency ω and the wave vector k parallel to the interface for all the eigenmodes. The modes that are confined in the dielectric region exhibit three discrete bands labelled as I, II, III, respectively. All these modes have TM polarization with magnetic field perpendicular to the wave propagation direction. The modes in band II are of particular interest because a significant portion of their dispersion relation lies above the light line of air. Consequently, externally incident light can couple to this band when one of the metal regions is of finite thickness. When k approaches infinity, $\omega_{II}(k)$ (i.e., the dispersion frequency of band II as a function of k) approaches $\varepsilon_{sp} = \varepsilon_p \Big/ \sqrt{1+\varepsilon_{dielectric}}$. At $k = 0$, $\omega_{II}(k=0)$ varies with the thickness d of the dielectric region, and coincides with ω_{sp} when

$$d = \frac{2\varepsilon c}{\varepsilon_{sp}} \varepsilon \frac{1}{4\sqrt{\varepsilon_{dielectric}}}$$

In this case, a full calculation shows that band II becomes almost completely flat (Fig. 1). For incident light at a given wavelength, the wave vector k is determined by the incidence angle. Such a flat dispersion band, therefore, indicates that the resonance occurs approximately at the same wavelength for all incidence angles. Further calculations indicate that such omndirectional resonance in fact persist in real metal systems [1].

III. SUBWAVELENGTH WAVEGUIDES

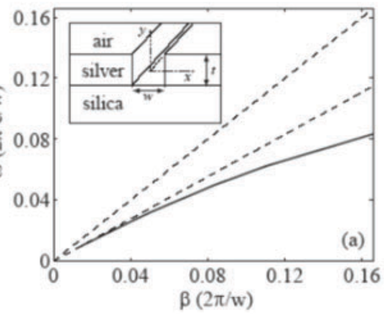

Fig. 2. Dispersion relation of a plasmonic slot waveguide.

Waveguide structures which support highly-confined optical modes are important for achieving compact integrated photonic devices. In particular, plasmonic waveguides have shown the potential to guide subwavelength optical modes. Several different three-dimensional plasmonic waveguiding structures have been proposed. However, these structures support a highly-confined mode only near the surface plasmon frequency. In this regime, the optical mode typically has low group velocity and short propagation length. Here we investigate the characteristics of the bound optical mode supported by an air slot in a thin metallic film deposited on a substrate (inset of Fig. 2) [2]. This structure is hereafter referred to as a plasmonic slot waveguide. Of particular interest is the regime where the dimensions of the slot are much smaller than the wavelength. We show that such a structure supports a fundamental bound mode with size almost completely dominated by the near field of the slot over a wide range of frequencies. The size of this mode can be far smaller than the wavelength even when its effective index approaches that of the substrate. In addition, the group velocity of the mode is close to the speed of light in the substrate and its propagation length is tens of microns at the optical communication wavelength. Thus, such a waveguide could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices. Finally, we note that the existence of the bound mode results from the finite negative dielectric constant of metals in the optical wavelength range. In fact, it is known that its microwave counterpart does not support a bound mode.

III. METAMATERIAL WITH DESIGNABLE DIELECTRIC CONSTANT

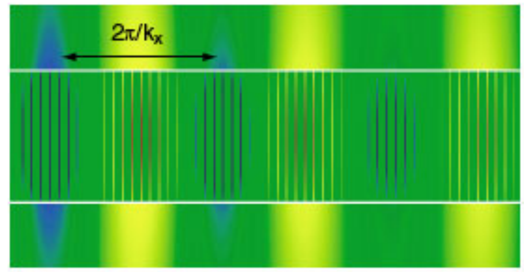

Fig. 3. Guided mode in a metal slit array.

Recently, there has been great interest in exploiting subwavelength resonances in metallic structures to create artificial materials with unusual effective electromagnetic responses. Notable examples include high-impedance surfaces used as an antenna substrate, negative refractive index metamaterials, effective surface plasmon behavior on perfect metal surface with gratings, and effective bulk plasmon behavior in thin-wire structures. Here, we show that a perfect metal film with a periodic arrangement of cut-through slits can be regarded as a dielectric slab with a frequency independent effective refractive index [3]. The effective index in this system is entirely controlled by geometry, and indices that are arbitrarily high can be straightforwardly synthesized. Such a capability is potentially important for miniaturization of optical or electromagnetic devices and for improving resolution in imaging. More fundamentally, the refractive index is commonly regarded as an intrinsic material property that is directly related to the underlying electronic states. By pointing out that the refractive index can be controlled by geometry only, and that ranges of large refractive index that are not previously accessible can in fact be generated with metamaterials, this work adds evidence to the important potential of replacing electronic states with subwavelength electromagnetic resonances, which could open up a new world of possibilities in optical physics.

IV. REFERENCES

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