Enhanced Transmission Into Layered-Plasmonic Metamaterials Through K-Space Harmonic Coupling

(Invited Paper)

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***Abstract*—Coupled plasmonic-waveguide metamaterials are of great interest to researchers investigating negative refraction and left-handed media at optical frequencies. These structures support backward waves along the planes of the layers and can negatively refract light beams incident at all angles. Although they are simple and easy to fabricate, low coupling efficiencies across the end-fire interface (the facet perpendicular to the layers) have been reported. In this paper, we propose a method to enhance the transmission based on knowledge of the power distribution of all Floquet-Bloch harmonics in k-space—information which cannot be obtained from either conventional EFC analysis or effective medium theory. We use this method to show two examples of tailored wave excitations that improve the coupling efficiency by a factor of up to forty times that of a normally incident plane wave.**

I. Introduction

In 1968, Veselago introduced a hypothetical simple medium with simultaneously negative permittivity ϵ and permeability μ [1]. He showed that this medium supported left-handed plane waves (waves in which the electric field, magnetic field, and wave vector formed a left-handed triad and phase and group velocity were anti-parallel) and could be described by a negative index of refraction. If such a medium could be physically realized, many exotic phenomena like negative refraction and flat lensing would suddenly be accessible. Recently, it has been shown that metamaterials composed of coupled plasmonic waveguides (which support backward waves in the plane of the layers) have features that resemble those of a Veselago medium at optical frequencies. These metal-dielectric-metal-dielectric-metal (MDMDM) periodic structures exhibit all-angle negative refraction of a polarized light beam and have a spherical equi-frequency contour (EFC) consistent with an effective three-dimensionally isotropic negative index of refraction $n = -1$ [2], [3].

Close analysis of the detailed electromagnetic field distribution throughout the structure, however, reveals anisotropic wave dynamics that undermine this approximation. In [4] and [5], we have used spatial frequency maps of power flow to show that comparisons of the MDMDM structure to the Veselago medium should only be made for propagation parallel to the layers (in-plane). Although negative refraction of power occurs for propagation across the layers (out-of-plane), the phase cannot be defined, and wave propagation is ultimately governed by right-handed high-order spatial frequency components. This analysis technique goes beyond traditional EFC analysis and effective medium theory by expanding the complete electromagnetic fields to their Floquet-Bloch harmonics, pairing electric and magnetic field harmonics, and mapping the resulting plane-wave harmonic Poynting vectors across k-space. In this mapping, we can observe that in general, fields are composed of a mixture of Floquet-Bloch harmonics in which the Poynting vector of each individual harmonic is not aligned to the net power flow and can carry significantly more power than the fundamental harmonic.

In this paper we show that knowing the distribution of power flow across all harmonics can enable significantly enhanced power coupling into the MDMDM structure than what has been previously reported [3]. High coupling efficiency results from choosing a wave excitation that couples to the dominant power spectral harmonics rather than the fundamental (as suggested by effective medium theory).

II. Enhanced Transmission Through Harmonic Coupling

The propagating modes within the MDMDM structure can be mapped to a set of plane-wave harmonics in k-space by taking the spatial Fourier transform of the fields. The resulting harmonics all lie along an axis perpendicular to the layers and share a common attenuation factor equal to the imaginary component of the fundamental Floquet-Bloch wave vector $\mathbf{k}_{\mathrm{FB}}$. Details of this procedure can be found in [5].

Figures 1 and 2 show spatial power maps for MDMDM modes propagating with power flow perpendicular to two different interfaces. In Fig. 1 the interface is perpendicular to the structure layers while in Fig. 2 the interface makes an angle of 45° to the layers (i.e. the MDMDM structure is tilted). In both cases, we can observe that the fields consist primarily of plane wave components carrying power outside the first Brillouin zone. In fact, less than 1% of the total power is carried by the fundamental component in either the flat or tilted MDMDM structure. It is therefore not surprising that a normally incident plane wave, which phase-matches to the fundamental, would not couple power effectively into the MDMDM mode despite homogeneous effective medium models suggesting otherwise.

The spatial frequency maps suggest that transmission into the MDMDM structure could be significantly enhanced if the incident wave were matched to one or more of the dominant higher-order harmonics. Although repeated zone

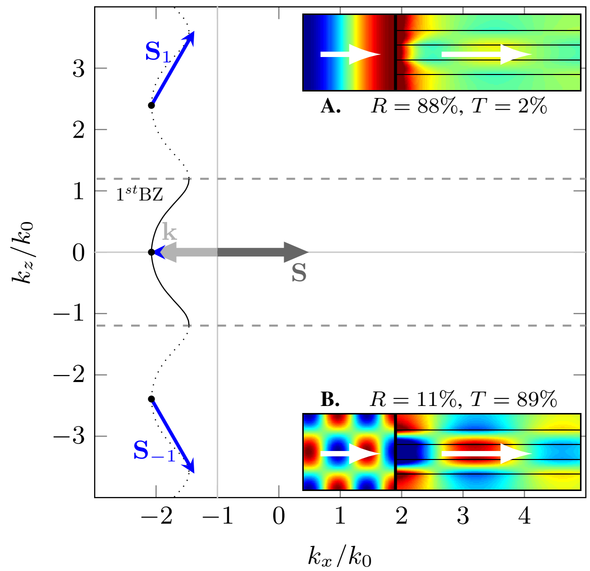

Fig. 1. The k-space map for in-plane propagation through the MDMDM structure. The blue arrows represent the Poynting vectors of each harmonic while the EFC corresponds to modes consistent with an interface perpendicular to the layers. Insets A and B show the incident and transmitted magnetic fields for a normally incident plane wave and a pair of obliquely incident plane waves, respectively. White arrows have been provided to indicate the direction of the average power flow, while the reflected and transmitted power as a percentage of the incident power is indicated by R and T.

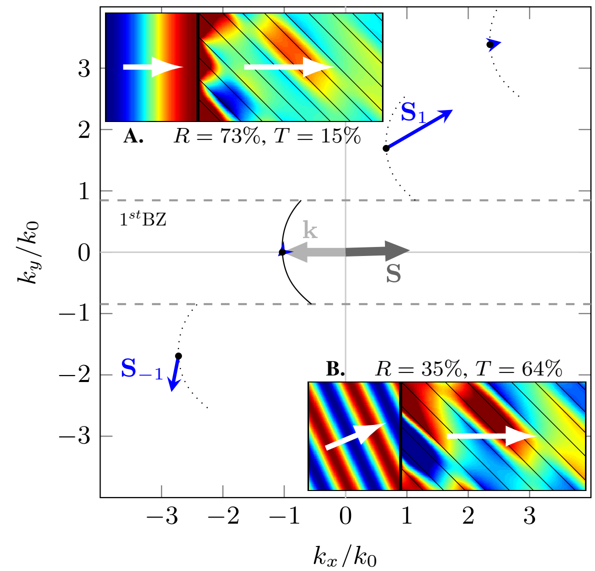

Fig. 2. The k-space map for propagation through the MDMDM structure at an angle of 45° to the layers. The interface was also oriented at 45° so this mode could be excited by a normally incident plane wave (inset A). The EFCs correspond to modes consistent with this interface. Inset B shows the fields given a single oblique plane-wave excitation of the same normal mode.

diagram analysis predicts that a mode could be excited through tangential wave vector matching to any of its harmonics, each harmonic is electromagnetically indistinguishable and no one harmonic can be given preference over another. Spatial power maps, by contrast, provide information about each harmonic's contribution to the total power flow, which immediately reveals which harmonics to use for higher coupling efficiency. For example, the k-space map in Fig. 1 shows that the two first-order harmonics ($k_y = \pm 2.4k_0$) carry 94% of the total power, implying that an incident wave that was matched to these harmonics would like have higher transmission efficiency.

This hypothesis was tested using full-wave transmission and reflection simulations in COMSOL Multiphysics using MDMDM structure specifications taken from [2]. Inset A in Fig. 1 shows the incident and transmitted transverse magnetic field given a plane wave normally incident from free space. Inset B shows the fields given a carefully chosen incident wave excitation tailored to couple to the first two high-order harmonics. Two oblique plane waves are incident at $\pm 53°$ from a high-index source medium ($n = 4$ and $\eta = 86\,\Omega$), providing over forty times the power transmitted into the structure and one eighth the reflected power as in inset A. The insets in Fig. 2 show the magnetic field for transmission into the MDMDM structure where the layers are oriented at 45° to the interface. Inset A shows normal plane-wave incidence from free space, while inset B shows an oblique plane wave incident at 25° from a high-index source medium ($n = 4$ and $\eta = 201\,\Omega$) designed to couple to the dominant $k_y = +1.7k_0$ harmonic. In this case transmission increases by a factor of four while reflections are cut in half. Note that all four insets plot the incident fields in the source region (left of the MDMDM layered region) and the transmitted fields in the MDMDM region. The reflected fields have been omitted for clarity.

III. Conclusion

The dramatic improvement in transmitted power into the MDMDM structure demonstrates the benefit of using k-space analysis to tailor the incident field to obtain highly efficient excitation channels across interfaces. By coupling the incident wave directly to the dominant spatial harmonic or harmonics, transmitted power levels were increased by up to forty times, with reflected power reduced accordingly. This further evidences the power of spatial maps of power flow as a tool to study the behaviour of electromagnetic propagation through metamaterials.

References

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