Slowing light by exciting the fundamental degeneracy oscillatory mode in both plasmonic and all-dielectric waveguides with negative refractive indices

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***Abstract*— We demonstrate the slowing light effect by exciting the negative Goos–Hänchen effect originating from the fundamental degeneracy oscillatory mode within negative refractive waveguides (NRWs). In the work, we construct three kinds of metamaterial-base NRWs, including an anisotropic plasmonic waveguide operated at multiple incidences, a discrete dielectric metamaterial waveguide, and a monolithic tapered dielectric metamaterial waveguide, and all of them successfully present slowing and even stopping light effect. The experimental demonstration is further confirmed by scrutinizing the distributions of E-field and power flow in simulation. Moreover, the effective indices of the NRW are retrieved by the theoretical analysis and then are affirmed by finite element simulation. The experimental result agrees the two simulation results well and so does the theoretical analysis**

Keywords*— slowing light; negative Goos–Hänchen effect; degeneracy oscillatory mode; negative refractive waveguides

Till now, there are various methods to slow and even to stop light, for example, electromagnetic induced transparency (EIT) due to quantum interference [1], plasmonics analogue EIT effect from the coupled bright and dark atoms [2], photonic crystals with negative Goos–Hänchen effect [3], and negative refractive metamaterial waveguides (NRMW) for both the surface plasmon polariton (SPP) mode and the oscillatory mode [4]. However, there appear certain disadvantages from these methods, such as a non-solid state device for quantum EIT effect, narrow operating bandwidth for both plasmonics analogue EIT effect and photonic crystals. Hence, it is the NRMW, the most promising candidate that supports both the SPP mode (slow wave) and the oscillatory mode (fast wave), to slow or even to stop light. The SPP/oscillatory modes of the NRMWs, which are composed of a core material with negative refractive index sandwiched by two cladding materials with positive refractive indices, render incident propagating light detouring around the interfaces between the core and the cladding layers within the waveguides and eventually present zero propagation distances as well as zero effective group velocities. To date, many cases of SPP modes in the NRMWs are widely studied and investigated in both theoretical modeling [4] and numerical simulations [3,6], suggesting the slowing light effect by confining photons at the critical thickness of the waveguide, but the SPP modes of the NRMWs still suffer from their sensitivity to the surface roughness of the interfaces between the core material and the cladding materials due to enormous field intensity distributions at the interfaces [5].

Rather, the propagating waves in the oscillatory mode of the NRMWs experience huge negative Goos–Hänchen effects to obtain zero effective group velocity and distribute its field intensity in the body of each layer of the NRMWs instead of localizing at the interfaces. Thus, the oscillatory mode in the NRMWs supports the slowing light effect without sensitivities to the interface roughness. Based on these properties, it is very convincing to experimentally demonstrate the oscillatory mode in the NRMWs and design a practical slowing light device. And so far, although many researchers demonstrate the slowing light effect both in simulations and in the experiments [5,7], there are no further discussions about the exact supported propagating modes in the NRMWs. Herein, we constructed three kinds of metamaterial-base NRWs, including an anisotropic plasmonic waveguide operated at multiple incidences (Fig. 1) [8], a discrete dielectric metamaterial waveguide (Fig. 2), and a monolithic tapered dielectric metamaterial waveguide (Fig. 3), and all of them successfully present slowing and even stopping light effect. The experimental demonstration is further confirmed by scrutinizing the distributions of E-field and power flow in simulation. Moreover, the effective indices of the NRW are retrieved by the theoretical analysis and then are affirmed by finite element simulation. The experimental result agrees the two simulation results well and so does the theoretical analysis.

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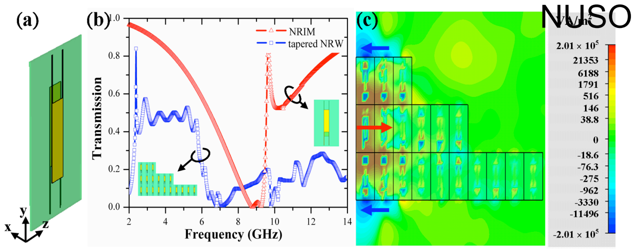
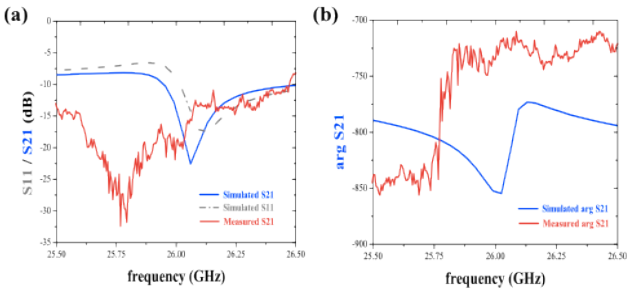


Fig. 1. (a) The scheme of the building block of an anisotropic negative refraction index medium (NRIM) and a negative refraction waveguide (NRW) (b) The transmission coefficients for the NRIM (red curve) and for the NRW (blue curve). The red curve demonstrates a transmission peak at 9.65 GHz and it turns out to be a transmission dip for blue curve at 9.83 GHz, suggesting that the NRW indeed supports the slowing light effect. (c) The distribution of power flow within the tapered NRW at 9.83 GHz. The opposing signs (the red arrow for forward and the blue arrows for backward propagation) of the power flow in the core material and in the cladding materials suggest the occurrence of a huge negative Goos-Hänchen effect within the tapered NRW. The incident light is detoured around the interfaces between the anisotropic NRIM and air and the energy is mainly trapped within the NRW.



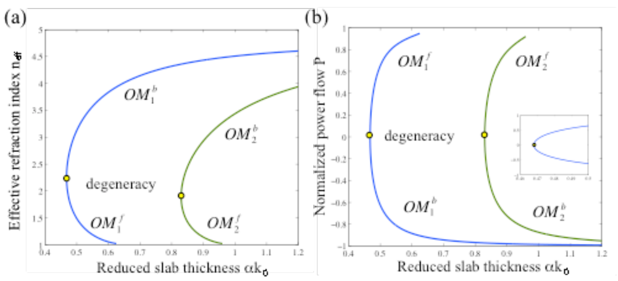


Fig. 2. (a) The simulated transmission coefficient (blue) and measured transmission coefficient (red) curves in dB scale excited by the WR 42 waveguide operated within frequency range from 18.0 to 26.5 GHz. (b) The transmittance phase change in both measurement (red) and simulation (blue). The two are consistent with each other. The schematic diagram for the variation of effective refraction index (c) and normalized power flow (d) with the reduced slab thickness. The parameters (-4.8,-4.8), (1,1), and (1,1) for permittivity and permeability of each layer is used. From (c), the effective refraction index 2.25 of the LHMW suggests the mechanism of the slow effect stemming from the negative Goos-Hänchen effect instead of large group refraction index. From (d), the critical thickness where the effective group velocity is zero is demonstrated. As shown in the inset of (d), we obtain identical reduced slab thickness 0.467 compared to the one in the CST with α=0.857 and k_0=546.95

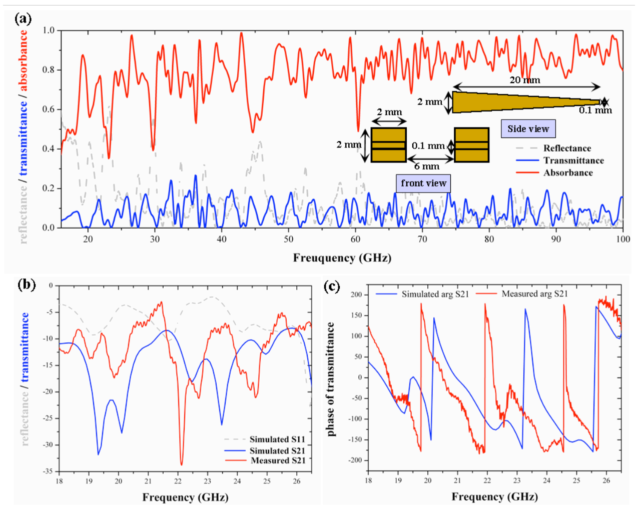


Fig. 3. (a) The reflectance (gray), transmittance (blue) and absorbance (red) of the left-handed metamaterial waveguide (NRMW). The inset of (a) indicates the dimensions and periodicity of the NRMW in the front and top view. (b) The simulated transmittance (blue) and measured transmittance (red) curves in dB scale excited by the WR 42 waveguide operated within frequency range from 18.0 to 26.5 GHz. Multi transmittance dips are observed in the spectra which suggest the frequencies where the negative Goos-Hänchen effect occurs. (b) The transmittance phase change in both simulation (blue) and measurement (red). The two are consistent with each other with an offset of less than 1.5 %.

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