Nano-optics with electron beams: probing the dispersion and local density of states of metamaterials with 10 nm resolution

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Abstract

We introduce a new technique, angle- and polarization-controlled cathodoluminescence imaging spectroscopy, to determine the dispersion and local density of states in photonic metamaterials. By using a 1-10 nm diameter focused electron beam as a point dipole source for the excitation of optical modes, that are then detected in the far-field by a parabolic mirror integrated in the microscope, we determine the full dispersion diagram of metal-insulator-metal waveguides with different dimensions and geometries. We accurately map the plasmonic standing waves, and collect the angle-resolved radiation patterns, leading to the direct demonstration of waveguides zero-phase advance, corresponding to n=0, in the 500-1800 nm spectral range

1. Introduction

Metamaterials are materials with artificial electromagnetic properties defined by their sub-wavelength structure rather than their chemical composition. Here, we introduce a new class of metallodielectric materials composed of a three-dimensional architecture of strongly coupled plasmonic waveguides. By engineering the dispersion in these structures light can be manipulated and controlled in unique ways.

2. Metamaterial building blocks

The basic building block in our structures is the plasmonic metal-insulator-metal waveguide, of which the dispersion can be tuned by varying the dielectric layer thickness.[1] These structures are particularly interesting because the coupled plasmon waves can be excited electrically.[2] When rolled up into a coaxial geometry, the dispersion of these waveguides can be further controlled by engineering the coaxes‘ inner and outer diameters.[3] In a 3-dimensional arrangement of coupled coaxial plasmonic waveguides (see Fig. 1(a)), dispersion can be controlled in three dimensions. The refractive index in such a material is tunable between -10 and + 10, and the figure of merit is as high as 10. Fully isotropic negative-index behavior can also be achieved in a one-dimensional geometry of coupled pairs of plasmonic metal-insulator-metal waveguides.[4] Such structures can be made using focused ion beam milling of ultra-thin membranes (see Fig. 1(b)). Optical refraction experiments on fabricated microprisms show clear negative refraction at a wavelength of 365 nm.

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3. Cathodoluminescence imaging spectroscopy

With the light propagating and confined within these metallodielectric structures, a key question is how these modes can be addressed from the outside, so that their dispersion and local density of states, two key parameters describing propagation and confinement, can be measured. In this paper we introduce a new technique, cathodoluminescence imaging spectroscopy, to determine these quantities. The metamaterial structures are excited by a 30 keV electron beam, focused on the sample surface to a spot size of 1-10 nm. The incident point charge, together with its image charge in the substrate forms a broadband point dipole source that, according to Fermi's Golden Rule, excites the metamaterials' modes over a broad spectral range. The radiation from these modes, that occurs by scattering at end facets of the structures, or through antenna radiation of the resonant modes, is collected in the far field by a parabolic mirror and imaged onto a CCD detector. In this way, spatial maps (resolution 10 nm) of the plasmonic resonant mode intensities can be determined spectra from which the plasmon wavelength and hence dispersion can be directly derived. Information of the modal phase advance is acquired by collecting the angle-resolved radiation patterns.

4. Results

We apply this technique to coaxial Ag/SiO_2/Ag waveguides fabricated using deposition and focused ion beam milling and directly demonstrate that these structures, at the cutoff frequency, show zero phase advance of light, corresponding to an effective refractive index n=0. At cutoff, the enhanced density of optical states is directly observed from a peak in the electron-beam induced emission spectrum. The cutoff frequency can be tuned throughout the entire visible-infrared spectral range (400-1800 nm) by varying the geometry. Applications of these waveguides in planar integrated circuit architectures will be discussed.

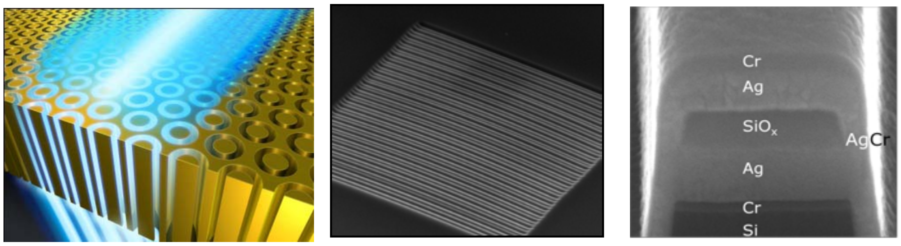

Fig. 1 (a) Schematic of metamaterial composed of coupled coaxial plasmonic waveguides, (b) experimental metamaterial microprism composed of coupled Ag /Si_3N_4/Ag plasmonic waveguides, showing n=-1.0 at λ=380 nm, (c) Cross section of coaxial plasmonic waveguide with n=0 tunable between at λ=400-1800 nm.

References

1. *Plasmon slot waveguides: towards chip-scale propagation with subwavelength-scale localization*
J.A. Dionne, L. Sweatlock, H.A. Atwater, and A. Polman, Phys. Rev. B **73**, 035407 (2006)
2. *A silicon-based electrical source of surface plasmon polaritons*
R.J. Walters, R.V.A. van Loon, I. Brunets, J. Schmitz and A. Polman, Nature Mater. **9**, 21 (2010)
3. *A single-layer wide-angle negative index metamaterial at visible frequencies*
S.P. Burgos*, R. de Waele*, A. Polman, and H.A. Atwater, Nature Mater. **9**, 407 (2010)
4. *Three-dimensional negative index of refraction at optical frequencies by coupling plasmonic waveguides*
E. Verhagen, R. de Waele, L. Kuipers, and A. Polman, Phys. Rev. Lett. **105**, 223901 (2010),