Metamaterial polarization spectral filter: Isolated transmission line at any prescribed wavelength

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We demonstrate that a narrowband spectral filter with a ripples-free isolated transmission peak and wide acceptance angle can be constructed exploiting polarization properties of a metal film patterned on the subwavelength scale. Its transmission band can be engineered to be anywhere from the visible to microwaves. © *2011 American Institute of Physics*. [doi:10.1063/1.3656286]

One of the most elegant polarization spectral filters exhibiting a single isolated transmission line with a large acceptance angle was suggested by Henry.[1] Its functionality depends on the energy exchange between two orthogonally polarized modes in a birefringent crystal in the proximity of the spectral point λ_0 where birefringence $\partial n = n_o - n_e$ changes its sign, see Fig. 1(a). At this wavelength, known as the "isoindex wavelength" birefringence vanishes and the crystal becomes isotropic. At wavelengths away from the isoindex point, where birefringence is substantial, two orthogonally polarized waves, the "ordinary" wave with refractive index n_o and "extraordinary" wave with n_e, are good eigenstates of the crystal and energy exchange between them does not take place. If the crystal is placed between two crossed linear polarizers aligned along these eigenpolarizations, no light will be transmitted through the device. However, near the isoindex point, a small perturbation can disturb the eigenstates and light passing through the crystal changes its polarization state: at this wavelength, the crystal sandwiched between crossed polarizers will transmit light.

Torsional stress, magnetic field, or natural optical activity (circular birefringence) of the crystal itself could mix up the orthogonal polarization eigenstates and thus could act as the perturbation.[1–4] For instance, if natural optical activity rotates the polarization state of light, a high background- and ripple-free transmission line centered at the isoindex point will be observed, see Fig. 1(a). The filter's transmission line width $\Delta\lambda$ depends on the dispersion of birefringence $\partial n/\partial\lambda$ at the isoindex point: $\Delta\lambda = (\lambda_0/2L)/(\partial n/\partial\lambda)$, while the optimal length of the crystal L is governed by the condition that circular birefringence (optical activity) rotates the polarization state of light by $GL = 90°$. Here, G is the specific rotary power of the crystal at the isoindex point. In a good quality filter, the birefringence increases rapidly away from the isoindex point, while optical activity has a non-zero value.

Isoindex filters have been extensively studied and demonstrated with different crystalline media,[1–11] most notably with CdS under torsion stress and $CuAlSe_2$ exploiting its natural optical activity. In crystal-based isoindex filters, the transmission wavelength is prescribed by the crystal itself, for instance, in CdS, it is at $\lambda_0 = 523$ nm, while in $CuAlSe_2$, it is at $\lambda_0 = 531$ nm. However, only a few isoindex crystals have been identified so far. Thus, wavelengths at which isoindex crystals can be constructed are sparse and little is known about crystals with isoindex points in the infrared and beyond. Furthermore, isoindex crystals, which are often exotic compounds, are extremely expensive, which hampers their applications and technological proliferation.

Here, we show that the key element of the filter, the isoindex crystal, can be replaced by a metamaterial, an artificial electromagnetic medium consisting of a regular array of subwavelength resonators, which can be engineered to offer a narrow-band spectral filter at a prescribed wavelength anywhere from the microwave to the visible part of the spectrum. Moreover, we demonstrate that it is sufficient to use a

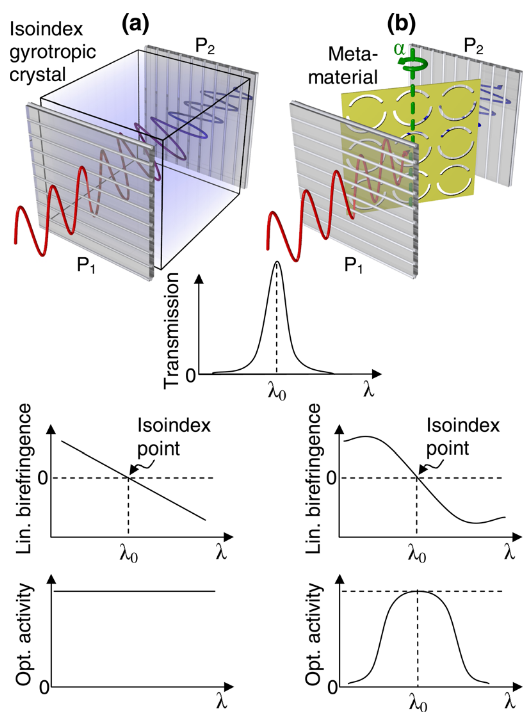

FIG. 1. (Color online) Isoindex gyrotropic spectral filters. (a) In conventional filters of this type, a uniaxial optically active birefringent crystal with accidental birefringence zero-crossing λ_0 is sandwiched between two orthogonal linear polarizers P_1 and P_2. The crystal birefringence must change sign at wavelength λ_0, while optical activity (circular birefringence) should remain non-zero. (b) In metamaterial-based isoindex spectral filters, planar metamaterial tilted with respect to the filter's optical axis replaces the crystal. The metamaterial exhibits strong resonant optical activity, which coincides with a birefringence zero-crossing isoindex point λ_0.

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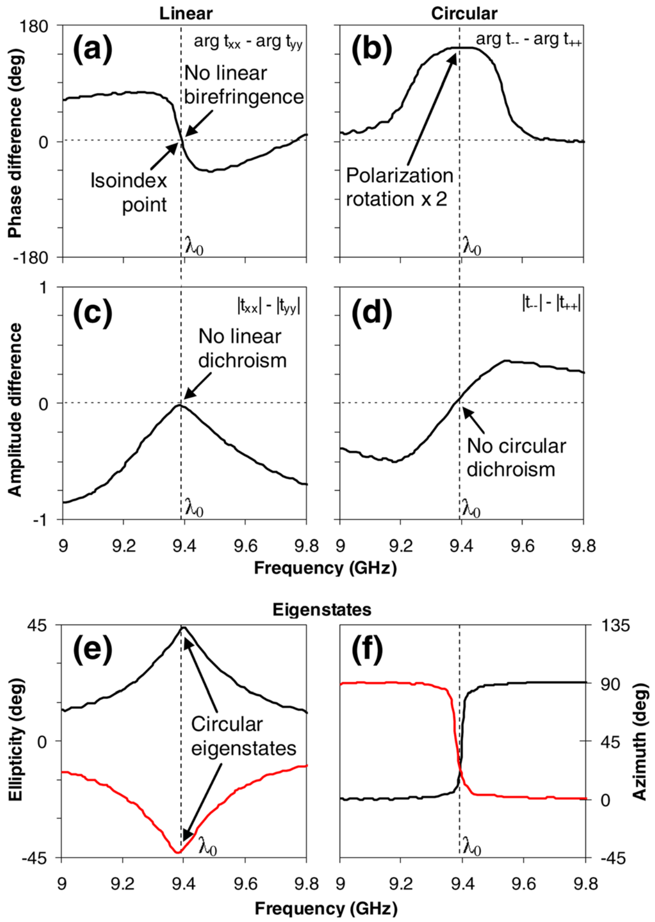

FIG. 2. (Color online) Metamaterial characteristics near the isoindex point. (a) Linear and (b) circular birefringence represented as differential phase delay for orthogonal polarizations. (c) Linear and (d) circular dichroism represented as differential transmission amplitudes. (e) Ellipticity angle and (f) azimuth of the metamaterial's polarization eigenstates. Circular eigenstates illustrate negligible linear dichroism and zero linear birefringence at the isoindex point. All quantities are plotted for $\alpha = 20°$ oblique incidence onto the metamaterial shown in Fig. 3(a). t_{ii} are the metamaterial's direct transmission coefficients for electric fields which are linearly polarized perpendicular (x)/parallel (y) to the metamaterial's symmetry axis or right (+)/left (−) circularly polarized.

single layer, planar metamaterial structure to achieve the filter (see Fig. 1(b)).

Indeed, in planar metamaterials birefringence can be easily derived from an asymmetry of the meta-molecule while the interplay between different modes of meta-molecular excitation can create a response with vanishing birefringence at certain isoindex wavelengths. This is routinely observed for metamaterials in all parts of the spectrum.[12] Perturbations that mix up the eigenmodes are less trivial to achieve. Natural optical activity is a prime choice here as it does not require application of torsional stress or magnetic field. Metamaterials with strong optical activity are well known and they are normally constructed from volume 3D meta-molecules.[13,14] However, they are difficult to manufacture, in particular for the optical part of the spectrum. Fortunately, an elegant solution exists where optical activity can manifest itself in planar metamaterials. This can take place for non-normal incidence onto arrays of meta-molecules lacking 2-fold rotational symmetry, such as asymmetrically split rings. Here, optical activity is allowed by a chiral arrangement of the incident wave vector and the low-symmetry metamaterial pattern.[15]

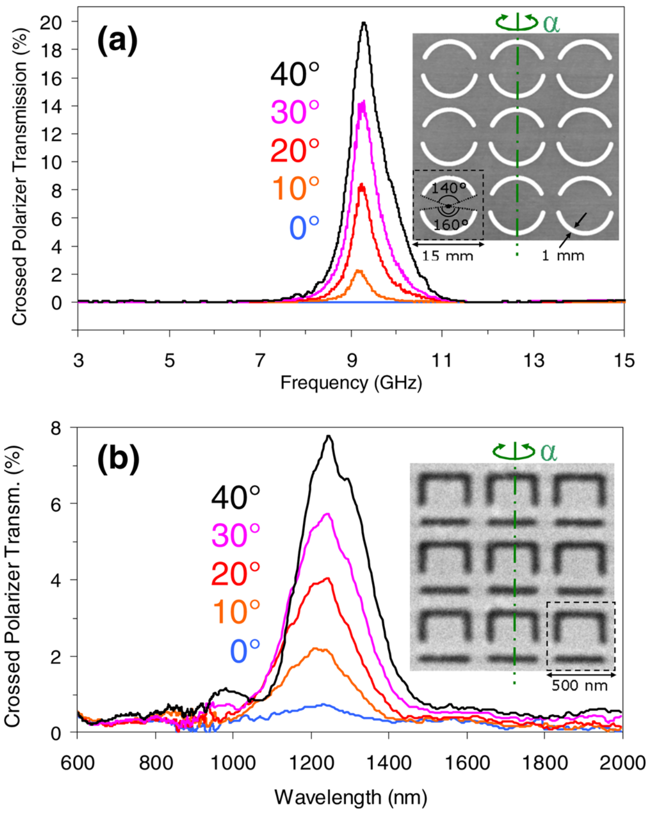

FIG. 3. (Color online) Metamaterial-based isoindex filters for microwaves and optics. Transmission characteristics of the (a) microwave and (b) optical filters for various angles of the metamaterial tilt α. The insets show fragments of the actual metamaterial patterns.

Such metamaterial-based filters, that we call metamaterial isoindex filters (MIFs), have been manufactured and studied for the microwave and optical parts of the spectrum. The microwave version of the metamaterial was an array of asymmetrically split ring apertures with a 15×15 mm^2 unit cell. It was milled in a self-standing 1 mm thick aluminum sheet (Fig. 3(a)). Each split-ring aperture had a 6 mm radius and consisted of 140° and 160° arc slits of 1 mm width. The photonic version of the metamaterial (Fig. 3(b)) was based on a rectangular-shaped split-ring pattern. The pattern's 50 nm wide slits were etched in a 30 nm thick gold film on a 500 μm thick fused silica substrate using electron beam lithography. Five metamaterial samples with respective unit cell sizes of 400, 425, 450, 475, and 500 nm were manufactured. The microwave filter was characterized in an anechoic chamber using linearly polarized antennas and a vector network analyzer while the performance of the optical filters was measured with a microspectrophotometer using dichroic linear polarizers.

At normal incidence, the split-ring pattern only allows two orthogonal linearly polarized eigenstates oriented parallel and perpendicular to the splits. However, there is a spectral point where linear birefringence and dichroism simultaneously vanish giving rise to the isoindex point, see Fig. 2. Our analysis shows that at this wavelength, the anisotropy, native to this metamaterial where the meta-molecules lack rotational symmetry, is canceled through the interference of two modes associated with the short and long sections of the ring.

Optical activity of the asymmetric structure is derived from resonant excitation of electric and magnetic dipole moments in each meta-molecule by the incident wave.[16] At oblique incidence, the induced electric and magnetic dipoles acquire scattering components that are orthogonal to the corresponding component of the incident wave.[15] As a result, our planar metamaterial exhibits optical activity at the resonance and the structure's two orthogonal linearly polarized eigenstates become coupled, in a way that mimics crystal-based isoindex filters, see Figs. 2(e) and 2(f). Here, the strength of the coupling is controlled by the metamaterial tilt angle α.

Fig. 3 shows transmission spectra of the microwave and optical MIFs measured for different tilt angles α. For $\alpha = 0°$, the filter is in the "OFF" state: transmission of the microwave device is essentially zero over the investigated spectral range of 3–15 GHz, as shown in Fig. 3(a). When the metamaterial is tilted relative to the optical axis of the filter, a narrow passband opens up at 9.25 GHz. The transmission increases rapidly with increasing tilt reaching 20% at $\alpha = 40°$. The bandwidth of the filter also depends on the tilt angle, increasing from 0.44 GHz at $\alpha = 10°$ to 0.81 GHz at $\alpha = 40°$.

Similar behavior has been observed for the optical version of the metamaterial polarization spectral filter. In the "OFF" state, its transmission remains well below 1% over the wide spectral range from 600 to 2000 nm, and a narrow transmission band appears at 1240 nm when the metamaterial is titled around its symmetry axis as shown in the inset to Fig. 3(b). The transmission level of the filter increases with the tilt angle and reaches about 8% at $\alpha = 40°$, while its bandwidth does not exceed 200 nm. Here, the lower quality factor of the transmission resonance relative to that of the microwave filter is explained by Joule losses in the metal structure, which are substantial in the optical part of the spectrum.

In contrast to isoindex filters based on natural crystals, the passband of MIFs can be engineered for any wavelength by simply rescaling the unit cell of the metamaterial array (see supplementary material[17]). The width of the band can also be controlled through metamaterial patterning. The control parameter here is the asymmetry of the split rings: for low loss materials reducing the asymmetry will result in a much narrower transmission band. The MIF passband's spectral width is mainly controlled by the band of resonant optical activity (circular birefringence), whereas the passband of crystal-based isoindex filters mainly depends on the dispersion of linear birefringence around the isoindex point. Furthermore, huge circular birefringence exhibited by a single-layer metamaterial element makes high-aperture MIFs easy to manufacture.

Alike crystalline isoindex birefringent filters, MIFs have a large field of view as the spectral position of the transmission line does not depend on the direction of incidence. However, transmission vanishes for light incident in the plane containing the metamaterial's symmetry axis and its surface normal. This unusual property could be exploited for blocking unwanted signals from certain directions.

In conclusion, we demonstrated that metamaterial isoindex filters can provide a background- and ripple-free narrow-band transmission line with tunable bandwidth and throughput efficiency anywhere from optical to microwave frequencies. Such filters, including their metamaterial elements and polarizers, can be easily fabricated using existing planar fabrication technologies. Moreover, recent progress in reconfigurable metamaterials[18–21] offers the opportunity to also change the transmission wavelength of the filter. We argue that given the unique combination of their narrow passband and wide field of view isoindex metamaterial filters could make a superior alternative to other filter technologies, in particular for sensing, lidar, and communication applications.

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