Metamaterial beats natural crystals in spectral filters: isolated transmission line at any prescribed wavelength

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Spectral filters are key components of telecommunication, imaging, sensor and spectroscopic devices. Optical filters are achieved though engineering of interferences in a complex multilayered structure, or by exploiting dispersion of absorption or anisotropy in natural media. In the microwave and terahertz regions frequency selective surfaces are used to provide spectral selectivity. While being extremely good in some of their characteristics, narrow-band interference filters suffer from a small acceptance angle, filters based on absorption or anisotropy depend on the availability of natural media to provide functionality at the required wavelength and frequency selective surfaces often show multiple and wide transmission bands. Here we demonstrate that a narrow-band 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.

We design our spectral filter taking inspiration from polarization optical filters which are widely know in optics. One of the most elegant polarization filters exhibiting a single isolated transmission line at a spectral position that is independent of the light's incidence angle on the filter 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 ripples-free transmission line centered at the isoindex point will be observed, Fig. 1(a). The filter's transmission line width $\triangle\lambda$ depends on the dispersion of birefringence $\partial n/\partial\lambda$ at the isoindex point: $\triangle\lambda = (\lambda_0/2L)/(\partial n/\partial\lambda)$, 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. To achieve a good quality filter the birefringence shall increase rapidly from the isoindex point, while optical activity shall have a non-zero value.

Isoindex filters have been extensively studied and demonstrated with different crystalline media [1–11], most notable 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 know 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 sub-wavelength 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 single layer, planar metamaterial structure to achieve the filter.

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 with metamaterials in all parts of

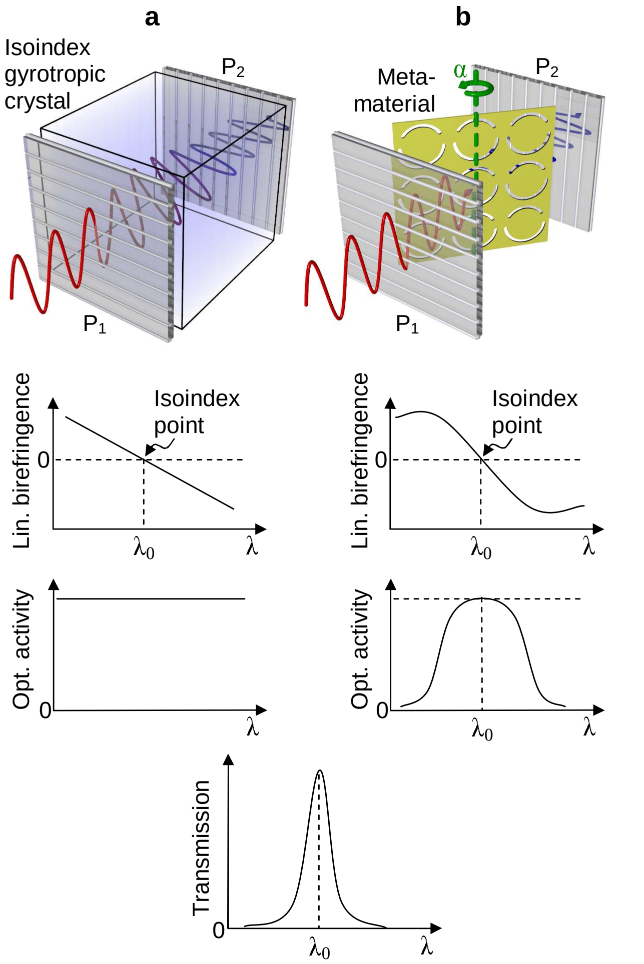

FIG. 1: **Isoindex gyrotropic spectral filters.** (a) In conventional filters of this type, a uniaxial optically active birefringent crystal with accidental birefringence zero-crossing λ_0 is sandwiched between two orthogonal linear polarizers P_1 and P_2. The crystal birefringence must change sign at 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 a birefringence zero-crossing isoindex point λ_0 on a background of strong resonant optical activity.

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, thee-dimensional meta-molecules [13, 14]. However, metamaterials with three-dimensional meta-molecules 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. Here optical activity is allowed by a chiral arrangement of the incident wave vector and the low-symmetry metamaterial pattern [15].

We have identified a class of birefringent planar metamaterials that show optical activity at the isoindex point. These metamaterials are arrays of asymmetrically split ring slits in a metal film. We have been able to demonstrate that when such a metamaterial structure is placed between a pair of crossed polarizers at some angle to the optical axis of the system (see Fig. 1(b)), a narrow-band, ripples-free spectral filter is formed. Such 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 unit cell of 15×15 mm^2. It was milled in a self-standing 1 mm thick aluminum sheet (inset to Fig. 3(a)). Each split-ring aperture had a radius of 6 mm and consisted of 140° and 160° arc slits of 1 mm width. The photonic version of the metamaterial (inset to Fig. 3(b)) was based on a rectangular-shaped split-ring pattern. The slits of the pattern had the width of 50 nm and 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 allows two orthogonal linearly polarized eigenstates oriented parallel and perpendicular to the splits. Although the pattern is inherently anisotropic, 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 rotation symmetry, is canceled through the interference of two modes associated with the short and long sections of the ring.

Optical activity of the structure is derived from antisymmetric currents on either side of the slits, which give rise to an overall magnetic dipole moment oscillating normal to the plane of the split rings [16]. At oblique incidence the magnetic dipole has a component orthogonal to the wave propagation direction and parallel to the polarization 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, exactly in the same way as in the crystal-based isoindex filter, see Fig. 2(e-f). Here the strength of the coupling is controlled by the angle α at which the metamaterial is tilted to the wave

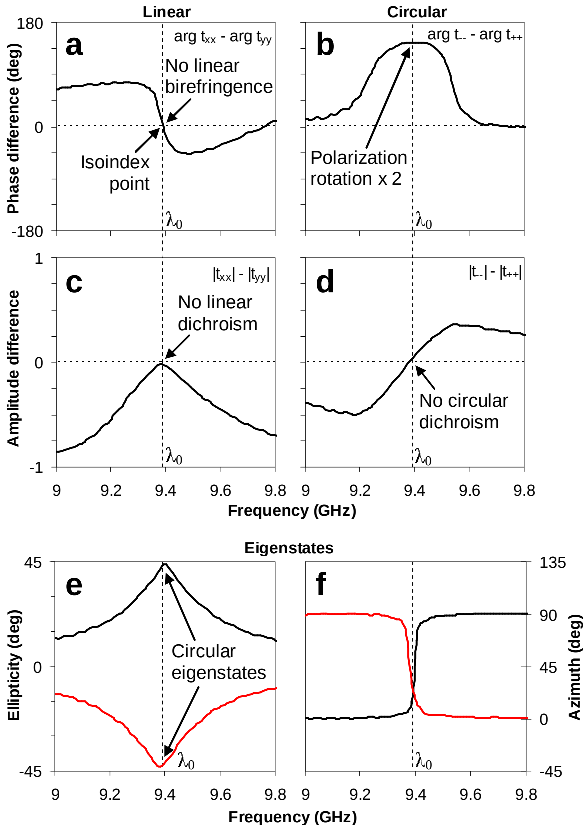

FIG. 2: **Metamaterial characteristics near the isoindex point.** (a) Linear and (b) circular birefringence represented as differential phase delay for orthogonal polarizations. (c) Linear and (d) circular dichroism represented as differential transmission amplitudes. (e) Ellipticity angle and (f) azimuth of the metamaterial's polarization eigenstates illustrate negligible linear dichroism and zero linear birefringence at the isoindex point: note that at this point the polarization eigenstates are circular. 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.

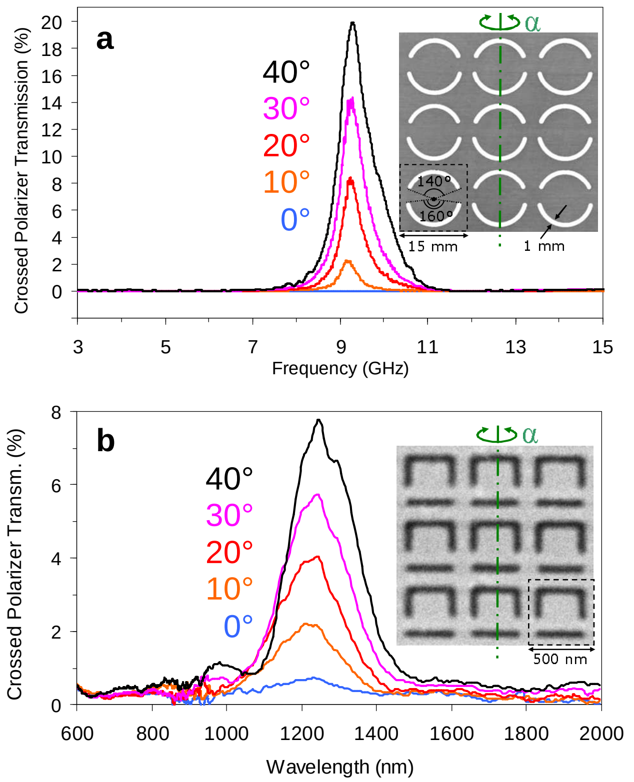

FIG. 3: **Metamaterial-based isoindex filters for microwaves and optics.** Transmission characteristics of the (a) microwave and (b) optical filters for various angles of the metamaterial tilt α. The insets show fragments of the actual metamaterial patterns.

propagation direction.

Fig. 3 shows transmission spectra of the microwave and optical metamaterial-based isoindex filters 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, 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 level of transmission increases rapidly with increasing tilt angle 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 isoindex 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 tilted 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 in comparison with that of the microwave filter is explainable by Joule losses in the metal structure which become substantial in the optical part of the spectrum.

In contrast to isoindex filters based on the natural crystals, the passband of MIFs can be engineered for any wavelength by simply re-scaling the unit cell of the metamaterial array. This is illustrated in Fig. 4 for the optical version of the filter, where its passband shifts from 1000 to 1240 nm when the size of the unit cell increases from 400 to 500 nm. 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. While in many natural isoindex crystals the birefringence zero-crossing is seen on a background of low dispersion optical activ-

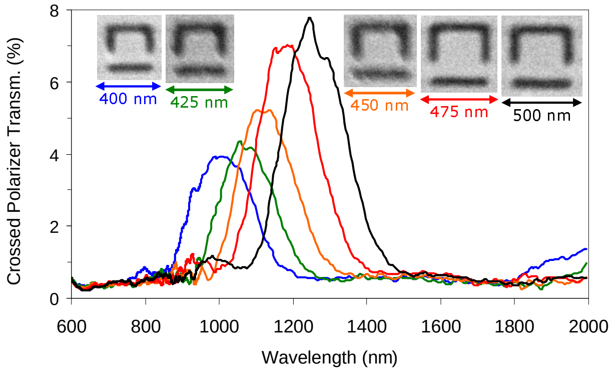

FIG. 4: **Isoindex filters for any wavelength.** Transmission spectra of metamaterial isoindex filters based on nanostructures with periods ranging from 400 nm to 500 nm. The angle of incidence is $\alpha = 40°$ in all cases. The insets show SEM images of each metamaterial's unit cell.

ity (circular birefringence), optical activity in asymmetric split-ring metamaterial is resonant which contributes to a narrow passband of the MIFs, compare Figs. 2(a-d). Furthermore, huge linear and circular birefringence exhibited by a single-layer metamaterial element makes high-aperture MIFs easy to manufacture.

In conclusion, we demonstrated that metamaterial isoindex filters, MIFs, can provide a background and ripples 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 [17–20] 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. Finally, there is also a complementary form of the filter where in a birefringent medium the polarization rotary power (optical activity) changes its sign at the some wavelength (isogyration point). Here a filter is achieved when the medium is placed between two circular polarizers [11]. A metamaterial suitable for the realization of such a filter is yet to be found.

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