Guided-mode resonant narrowband terahertz filtering by periodic metallic stripe and patch arrays on cyclo-olefin substrates

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We experimentally and theoretically demonstrate a class of narrowband transmissive filters in the terahertz spectrum. Their operation is based on the excitation of guided-mode resonances in thin films of the low-loss cyclo-olefin polymer Zeonor, upon which aluminum stripe and patch arrays are patterned via standard photolithography. The filters are engineered to operate in low atmospheric loss THz spectral windows, they exhibit very high transmittance and quality factors, compact thickness, and mechanical stability. The dependence of their filtering properties on the geometrical parameters, the substrate thickness and the angle of incidence is investigated, discussing the physical limitations in their performance. This class of filters provides a cost-effective solution for broadband source or channel filtering in view of emerging terahertz wireless communication systems.

Terahertz (THz) frequencies are increasingly capturing the attention of the scientific community, as they represent the less exploited region of the electromagnetic spectrum and they bridge the gap between optics and radiofrequency science and technology. This renewed interest was stimulated by significant improvements in the performance of THz emitters and detectors1, which paved the way for novel applications spanning from telecommunications20, cultural heritage4, and life sciences5, to security and defense6, or industrial non-destructive testing7. Therefore, the manipulation of THz wave propagation is of primary importance and much effort has been focused on the development of THz functional components such us polarizers, lenses, amplitude and phase modulators, sensors, and waveplates8–17. One class of such fundamental components are transmissive bandpass filters, which select radiation only in a narrow spectrum around a target frequency, a key property in numerous applications, e.g. ultrasensitive sensors18, compact spectrometers19, telecommunication20, or radar science21.

A state-of-the-art filter should ideally combine the following features: (i) high peak transmittance (low insertion losses), (ii) narrow linewidth (high quality factor Q), (iii) possibility for polarization-independent or tailorable polarization-dependent operation, (iv) low manufacturing cost, and (v) compact overall dimensions. The latter issue can be effectively addressed by employing thin metallic frequency-selective surfaces (FSS) or metasurfaces, which eliminate the need for dielectric multilayers and shrink the component dimensions. A long-established solution for transmitting only a confined set of THz frequencies is based on periodic FSS arrays of cross-shaped apertures, fabricated either as free-standing metallic films or patterned on thin substrates, which however result in rather broad resonances that cannot exceed Q values higher than 1522–30.

Recently, very high Q values have been observed in various metasurface designs with intentional symmetry breaking that excites trapped modes and leads to very sharp Fano resonances, with Q values even above 20035–38. Nevertheless, such high Q values are associated with very low peak transmittance and, in addition, these resonances are embedded in a non-flat background spectral response, which demonstrates very low out-of-band rejection with limited practical relevance. Moreover, since they are based on symmetry breaking, they inherently rule out polarization-independent operation. The latter also stands in the case of asymmetric single split rectangular ring elements, which were demonstrated as high-transmittance/high-Q bandpass filters at microwave frequencies39. High transmittance and narrow-linewidth THz transmissive filters have been also demonstrated based on interfering metasurfaces, which however result in a bandpass frequency comb and as such do not allow for out-of-band rejection40. In a different approach, extensive capabilities were demonstrated by designing...
terahertz plasmonic filters in the K-space, yet the resulting transmissive filters still show low out-of-band rejection, transmittance, and linewidth. In this work, all five aforementioned requirements are attained in a new class of THz transmissive selective filtering elements based on planar cyclo-olefin thin films. Contrary to the FSS-based established THz filters that typically transmit the THz wave through subwavelength apertures in a free-standing configuration, the operation of the proposed filters relies on the excitation of guided mode resonances (GMR) stemming from the coupling between waves on periodic structures with modes guided in a dielectric substrate. Although this concept is well-known in the design of optical filters and can be applied in lower frequency regions of the electromagnetic spectrum, provided a suitable low loss dielectric is available, it has been thus far only marginally exploited in the design of THz components. Song et al. experimentally demonstrated the validity of the approach in the design of bandpass filters at approximately 7 THz, though resulting in both low measured transmittance and quality factors due to the significant losses of the employed polyimide substrate. Recently, we have observed tightly spaced multiple GMR as a secondary effect in the response of FSS THz filters. Here, we experimentally demonstrate high-quality GMR transmissive filters able to filter THz radiation in a single operating narrow band, in contrast to the broadband response of standard FSS filters. We focus our design on the two THz low-loss wireless communication windows at 625–725 GHz and 780–910 GHz. These windows are extremely broad, 100 GHz and 130 GHz, respectively. Consequently, dedicated allocation of spectral channels will likely be necessary for different application or different operators. Hence, filters with narrow band and low insertion losses are strategic functional components.

The filters are fabricated by patterning an aluminum layer with a specific design on thin films of the very low-loss cyclo-olefin polymer Zeonor by standard UV photolithography. Low-cost and large-area electronic fabrication processes could be as well employed for ubiquitous deployment in the envisaged short range and indoor THz communication systems. Furthermore, in contrast to free standing metasurfaces, these devices are mechanically stable since they are supported by a polymer substrate. Thanks to the low loss of the substrate, they exhibit peak power transmittance above 85% for Q values experimentally measured as high as 70, along with increased out-of-band rejection. In addition, by proper design, both polarization-dependent and independent operation is demonstrated. Finally, a theoretical parametric analysis is presented to provide guidelines on the design of the presented filters and to investigate into their performance limitations. By engineering the design to extreme subwavelength features, we numerically demonstrate that it is possible to squeeze more than half of the incoming THz radiation within a narrow spectral band with a very high quality factor of about 140.

**Terahertz Narrowband Guided-Mode Resonant Transmissive Filters**

The layout of the proposed filtering components is schematically depicted in Fig. 1. A periodic configuration of Al stripes or rectangular patches is patterned on a thin film of Zeonor by standard UV photolithography. Low-cost and large-area electronic fabrication processes could be as well employed for ubiquitous deployment in the envisaged short range and indoor THz communication systems. Furthermore, in contrast to free standing metasurfaces, these devices are mechanically stable since they are supported by a polymer substrate. Thanks to the low loss of the substrate, they exhibit peak power transmittance above 85% for Q values experimentally measured as high as 70, along with increased out-of-band rejection. In addition, by proper design, both polarization-dependent and independent operation is demonstrated. Finally, a theoretical parametric analysis is presented to provide guidelines on the design of the presented filters and to investigate into their performance limitations. By engineering the design to extreme subwavelength features, we numerically demonstrate that it is possible to squeeze more than half of the incoming THz radiation within a narrow spectral band with a very high quality factor of about 140.

**Figure 1.** Schematic layout and definition of the geometrical parameters for the investigated GMR filtering elements based on (a) stripe and (b) square patch aluminum gratings patterned on the cyclo-olefin Zeonor. The thickness of the Al layer is 200 nm.
The most widespread configuration of GMR filters is based on all-dielectric gratings that operate in reflection, namely they block the transmittance at the GMR frequencies. However, when the grating acts not only as the diffractive element, but also as a highly reflective screen, high transmittance is achieved only in a narrow band around $f_0$, even for a deeply subwavelength thickness of the filter\cite{44,45}. This property is here exploited for the design of the proposed THz filters, by employing aluminum surfaces patterned on thin Zeonor substrates. The choice of the substrate material is instrumental in providing low intrinsic absorption losses and suitability for processing and handling of the manufactured filters.

Seven different chips, whose geometrical parameters and a brief summary of the key results are reported in Table 1, were designed and fabricated by UV photolithography\cite{15}. A 200-nm layer of aluminum was evaporated on the Zeonor substrates. A film with thickness $1.3 \pm 0.1 \mu m$ of the photoresist S1813 (Shipley) was spin-coated at 4000 rpm for 60 sec and then cured at a temperature of 115°C for 120 sec. The photolithography was carried out using a Karl Suss MA150 mask aligner ($\lambda = 365 \text{ nm}$, $I = 60 \text{ mW/cm}^2$). The samples were immersed in the developer MF319 for 50 sec, rinsed with DI water, dried with nitrogen and cured at 120°C for 5 min. Finally, the aluminum layer was wet-etched and the residual photoresist was removed with acetone and washed with isopropanol.

The experimental measurements were directly compared to theoretical finite-element simulations. These were performed an eigenfrequency analysis of the investigated structures in order to calculate the guided mode eigenfrequencies ($\beta f_\text{eig}$), as $\beta f_\text{eig} = \frac{\sqrt{n_p \mu_m}}{\mu_{eff}}$. Since material dispersion cannot be incorporated in a straightforward manner, in each studied case the Al permittivity is fixed at 0.9, which provides a good compromise between high peak transmittance, high quality factors, and increased out-of-band rejection. Larger fill factors would provide narrower band operation at the cost of reduced transmittance.

In the case of 2D patterns, we have opted for square lattices ($p_x = p_y = p$, $w_x = w_y = w$) in order to induce polarization-independent properties, as it will be demonstrated, working at the equivalent first-order diffraction modes ($\pm 1$, 0) and (0, $\pm 1$). The pitch value for chips #1–4 was selected such that the resonant frequencies lie in the center of the low-loss atmospheric attenuation windows envisaged for next-generation THz wireless communications, i.e. 625–725 GHz and 780–910 GHz\cite{1}. The rest of the chips (#5–7) were designed so as to provide a parametric study of their filtering properties. In all cases the fill factor of the metal layer, here defined as $F = w/p$, is fixed at 0.9, which provides a good compromise between high peak transmittance, high quality factors, and increased out-of-band rejection. Larger fill factors would provide narrower band operation at the cost of reduced transmission as discussed later on.

Figure 2 reports the power transmittance simulated and experimentally measured for chip #1. The filter exhibits very high transmittance ($T = 86\%$) and a 3-dB linewidth $\Delta f = 23 \text{ GHz}$ calculated at the full-width half-maximum (FWHM) around the resonant frequency $f_0 = 667 \text{ GHz}$, which corresponds to a quality factor $Q = f_0/\Delta f = 29$. We have numerically calculated that the insertion losses of 14% (0.65 dB) at the resonant frequency $f_0$ were compensated by the half-maximum (FWHM) around the resonant frequency. A film with thickness 1.3 μm was wet-etched and the residual photoresist was removed with acetone and washed with isopropanol.

| Chip | $p_x$ (μm) | $p_y$ (μm) | $w_x$ (μm) | $w_y$ (μm) | $d$ (μm) | $f_0^{FWHM}$ (GHz) | $f_0^{TDS}$ (GHz) | $Q_0^{\text{TDS}}$ (GHz) | $Q_0^{\text{ord}}$ (GHz) |
|------|------------|------------|------------|------------|---------|-------------------|-----------------|----------------------|----------------------|
| #1   | 390        | —          | 351        | —          | 100     | 666               | 667             | 29                   | 29                   |
| #2   | 288        | —          | 260        | —          | 100     | 848               | 850             | 34                   | 34                   |
| #3   | 288        | 288        | 260        | 260        | 100     | 848               | 850             | 34                   | 34                   |
| #4   | 390        | 390        | 351        | 351        | 100     | 666               | 667             | 29                   | 29                   |
| #5   | 340        | 340        | 306        | 306        | 100     | 743               | 745             | 748                  | 30                   |
| #6   | 438        | 438        | 394        | 394        | 100     | 605               | 606             | 606                  | 28                   |
| #7   | 288        | 288        | 260        | 260        | 40      | 986               | 985             | 984                  | 62                   |

Table 1. Summary of the geometrical parameters and performance metrics of the fabricated GMR filters. Superscripts ($T_{\text{ord}}$, $T_{\text{TDS}}$) and ($P_{\text{TDS}}$) stand for “Theoretical/eigenfrequency analysis”, “Theoretical/full-wave analysis” and “Experimental TDS measurements” respectively.

$$n_{eff} = \frac{|n|}{c} \frac{c}{f_0}$$

with $f_0$ being the resonant frequency and $c$ the speed of light in vacuum.
frequency at 850 GHz. was investigated in the case of chip #2, which is also based on Al-stripe lattice, and designed to have a resonant
x
results correspond to an impinging THz wave that is polarized perpendicularly to the Al stripes, i.e. along the
on-resonance, at the frequency of 600 and 667 GHz, respectively. The results are shown in Fig. 2(b) and they are
the device, we have calculated the profiles of the electric field components via FEM full-wave simulations off- and
only at the tips of the Al stripes 56, but also in the Zeonor substrate owing to the excitation of the resonant guide
reflected wave being also x-polarized. On-resonance, both components of the electric field are enhanced, not
incoming power is reflected, creating the expected standing wave pattern in the half-space above the device, the
C
THz filters induced by symme-
polarization-independent performance. The latter cannot be achieved in high-
comprises a square lattice of Al patches with the same pitch and patch width. It is evident that the pro-
mode. This profile corresponds to the first-order TM-polarized mode guided in a Al/Zeonor/air slab waveguide,
as discussed in ref.53. To further corroborate that the resonance indeed stems from coupling to guided modes, we
have plotted in Fig. 2 the profiles of the electric field components of the eigenmode calculated at 666 GHz via an
eigenfrequency analysis. The profile of the electric field excited by the planewave impinging on the filter at the
resonant frequency corresponds to the calculated guided mode in the substrate.

Figure 2. (a) Theoretically calculated and experimentally measured transmittance in the 0.3–3 THz range
for an Al-stripe GMR filter with \( p = 390 \mu m, w = 351 \mu m, \) and \( d = 100 \mu m \) (chip #1) and relevant performance
metrics. The inset shows a zoom around the resonant frequency of 667 GHz. The THz-TDS data above 2.5 THz
show some scattering owing to the decreasing signal-to-noise ratio of the instrument. (b) Relative electric field
components calculated via full-wave simulation off (600 GHz) and on (667 GHz) resonance. Note the different
scales in the two cases for the field enhancement. The field profiles on resonance match those of the guided
mode calculated at 666 GHz through eigenfrequency analysis.

Figure 3 shows the polarization-dependent transmittance of chip #2, compared to that of chip #3, which
comprises a square lattice of Al patches with the same pitch and patch width. It is evident that the pro-
posed stripe-based GMR filters transmit only one polarization, while their patch counterparts exhibit
polarization-independent performance. The latter cannot be achieved in high-Q THz filters induced by symme-
try breaking, which do not exhibit the \( C_4 \) symmetry of the square lattice GMR filters, as it can be visualized in
Fig. 4(b) that shows the photo and micrograph of the patterned surface of chip #3. The corresponding photos for
chip #2, characterized by the array of Al stripes, are shown in Fig. 4(a). The exact position of the resonant frequen-
cies depends mainly on the lattice pitch and the slab mode effective index that, for a fixed polymer material refrac-
tive index, is determined by the substrate thickness. For a given substrate film thickness, the resonant frequency
can be readily adjusted by properly tailoring the lattice pitch, as demonstrated in Fig. 5(a), which reports the
transmittance of chips #3–6 that correspond to four different pitch values. In all cases the peak transmittance stays
high, above 80%. The filter quality factor does not significantly vary and stays around \( Q = 30 \). Excellent agreement
between THz-TDS measurements and FEM simulations is observed. In addition, Fig. 5(b) investigates the effect
of the substrate thickness \( d \) for a fixed pitch \( p = 288 \mu m \). Samples were fabricated for two of the four investigated
cases, namely those with thicknesses \( d = 40 \) and \( 100 \mu m \). This selection was solely limited by the current availa-
bility of Zeonor films. In principle, for any substrate thickness the operation frequency can be tuned by properly
engineering the filter geometry. As the film thickness shrinks, the slab modal index drops and thus the resonant
frequency is shifted toward the limit \( f_{\text{max}} = c/p \), which is around 1.04 THz, also identifiable by considering the
For all the investigated films thicknesses, the power transmittance remains very high, between 80 and 90%. In particular, for $d = 40 \mu m$ (chip #7), this very high transmittance level is accompanied by a very high $Q$-factor value of 73.

In all cases examined so far, the fill factor of the metallic lattice was kept equal to 90%. By varying the fill factor, or equivalently the separation gap $s = p - w$ between adjacent Al patches, the effect on the filtering characteristics of chip #4 is shown in Fig. 6. As the gap shrinks, the resonance linewidth becomes narrower at the zero-transmittance point associated with Wood’s anomaly\textsuperscript{37}. For all the investigated films thicknesses, the power transmittance remains very high, between 80 and 90%. In particular, for $d = 40 \mu m$ (chip #7), this very high transmittance level is accompanied by a very high $Q$-factor value of 73.

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expense of reduced transmittance. However, even in the extreme case of gap values below 1 μm, i.e. almost 500 times smaller than the free-space wavelength, a significant amount of THz power still crosses the filter. This tight squeezing of electromagnetic radiation in extremely subwavelength slits and volumes has also been observed in non-diffracting gratings. Figure 6(b) provides a design rule for the selection of the gap value, in accordance with the target performance characteristics. It is remarked that for $s = 1.13 \, \mu m$ ($F = 0.997$), which can still be fabricated with standard UV photolithography without resorting to nanofabrication techniques, a quality factor as high as $Q = 147$ is obtained for 3 dB losses.

Figure 6. (a) Transmittance of a 2D GMR filter with $p = 390 \, \mu m$ and $d = 100 \, \mu m$, as a function of the gap $s = p - w$ in the Al patch lattice. (b) Dependence of the filter transmittance and quality factor on the gap value. For $s = 1.13 \, \mu m$ ($F = 0.997$), a $Q = 147$ is obtained for 3 dB losses.

Figure 7. Theoretically calculated, via FEM full-wave simulations, and experimentally measured transmittance of chip #1 as a function of the angle of incidence of the probe radiation plane-wave. The dashed lines indicate the resonant frequencies as calculated through the eigenfrequency analysis.

It is known that when a plane-wave impinges obliquely on a GMR filter the resonances for each diffracted mode split and follow two separate spectral branches as the angle of incidence $\theta$ of the probe radiation increases. Figure 6(b) provides a design rule for the selection of the gap value, in accordance with the target performance characteristics. It is remarked that for $s = 1.13 \, \mu m$ ($F = 0.997$), which can still be fabricated with standard UV photolithography without resorting to nanofabrication techniques, a quality factor as high as 147 is obtained for insertion losses of 3 dB. The combination of such high quality factors for single bandpass 50% filtering in transmission is a remarkable achievement in the field of THz technology, thanks to the careful electromagnetic design and the intrinsic low-loss properties of the substrate. The optimal selection of the fill factor value depends on the specific requirements of the target application.

It is known that when a plane-wave impinges obliquely on a GMR filter the resonances for each diffracted mode split and follow two separate spectral branches as the angle of incidence $\theta$ of the probe radiation increases. In particular, the phase-matching condition of Eq. (1) for the case of oblique incidence takes the form

$$\beta_{\text{eff}} = k_0 \sin(\theta) - \frac{2\pi}{p},$$

which gives two different solutions corresponding to $m = 1$ and $m = -1$. This is contrary to the case of normal incidence where the two modes are degenerate and as a consequence only one peak is observed in the transmittance spectrum. The effective indices of the two excited modes are given by
where the resonant frequencies \( f_{0}^{-} (f_{0}^{+}) \) are lower (higher) than \( f_{0} (\theta = 0^\circ) \).

We characterized chip #1 for \( \theta = 0^\circ , 2^\circ , 4^\circ , \) and \(6^\circ \) and plotted the obtained experimental results in Fig. 7. The resonance splitting is evident and in good agreement with theoretical modeling. The dashed lines indicate the frequencies corresponding to the eigenfrequency analysis problem, showing agreement better than 1.5 GHz, consistent with the results presented in Table 1. The tweaking of the angle of incidence using a rotation stage provides a means to dynamically tune the filter resonant frequency in a broad range and/or to achieve dual-band operation. For instance, the single resonance observed at normal incidence degenerates for \( \theta = 6^\circ \) into two resonances, with nearly identical transmission (\( T \approx 70\% \)), centered at 595 GHz and 683.5 GHz. Interestingly, these resonances are characterized by much higher quality factors (70 and 100, respectively) compared to the single one observed at normal incidence. This may find applications in filtering the transmit and receive communication channels using a single filter.

Conclusions

To sum up, a new class of THz filtering elements based on GMR in Al gratings supported by thin films of the low-loss cyclo-olefin polymer Zeonor is investigated, both theoretically and experimentally. The proposed filters combine a series of performance qualities, i.e. very high transmittance, narrow linewidth, increased out-of-band rejection, compact size, mechanical stability, and low manufacturing cost, which are unprecedented in the field of THz filter technology. Both polarization-selective and polarization-independent response is demonstrated by toggling between the dimensionality of the patterned Al lattice. Although part of the presented filters is specifically engineered for use at the low-absorption THz atmospheric windows, the general design procedure and rules are also discussed. Finally, the GMR-splitting under oblique illumination is also examined as a means to dynamically tailor the filter resonant frequency.

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Author Contributions
A-F. contributed to the theoretical analysis, fabricated and characterized the devices. D.C.Z. conceived the design and conducted the theoretical investigation. R.C. and R.B. analyzed the results and supervised the research. All authors participated in drafting and proof-reading the manuscript.

Additional Information
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