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Metamaterial composite bandpass filter with an ultra-broadband rejection bandwidth of up to 240 terahertz

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We present a metamaterial, consisting of a cross structure and a metal mesh filter, that forms a composite with greater functional bandwidth than any terahertz (THz) metamaterial to date. Metamaterials traditionally have a narrow usable bandwidth that is much smaller than common THz sources, such as photoconductive antennas and difference frequency generation. The composite structure shown here expands the usable bandwidth to exceed that of current THz sources. To highlight the applicability of this combination, we demonstrate a series of bandpass filters with only a single pass band, with a central frequency \( f_0 \) that is scalable from 0.86–8.51 THz, that highly extinguishes other frequencies up to >240 THz. The performance of these filters is demonstrated in experiment, using both air biased coherent detection and a Fourier transform infrared spectrometer (FTIR), as well as in simulation. We present equations—and discuss their scaling laws—which detail the \( f_0 \) and full width at half max (\( \Delta f \)) of the pass band, as well as the required geometric dimensions for their fabrication using standard UV photolithography and easily achievable fabrication linewidths. With these equations, the geometric parameters and \( \Delta f \) for a desired frequency can be quickly calculated. Using these bandpass filters as a proof of principle, we believe that this metamaterial composite provides the key for ultra-broadband metamaterial design. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4875795]
structure has the pattern on both sides of the 525 μm thick high resistivity silicon (HR-Si) substrate as shown in Fig. 1(b). The dimensions, σ values, central frequency (f₀), and full width at half max (Δf) of the filters studied are presented in Table I. For reference, these dimensions were originally chosen so that the higher order modes of the cross geometry would couple to lattice modes to eliminate unwanted transmission modes, although this ended up being unnecessary as discussed later.

To highlight the effect of the two constituent components in the structure, we present the simulated transmission curves of the cross, metal mesh, and full composite structure in Figure 2. The metal mesh is easily described as a combination of inductive and capacitive meshes. A capacitive mesh, which is simply a two dimensional array of metallic squares, works as a low pass filter. The complementary structure, called an inductive mesh, is a wire grid that functions as a high pass filter. Their combination, a metal mesh filter as shown here, has a pass band located at c/(nSi 2) and 22.5 THz. An examination of the current patterns at the gold-silicon interface suggests that these are higher order modes represented by taking the geometric ratio of metal area to unit cell area multiplied by the Fresnel transmission coefficient of silicon. In Figure 2, this ratio for each component is represented by the dotted horizontal line. When the cross element is added to the metal mesh, both the pass band and the high frequency content are substantially modified. The pass band is red shifted, resulting in the previously mentioned trapped mode excitation, and the high frequency content is reduced significantly. It is worth noting that even though the high frequency transmission of both the mesh filter and cross can be closely modeled by their geometric ratios, the composite structure shows an even greater extinction.

The dashed magenta line in Figure 2 is the simulated transmission of a single metamaterial element where the periodic boundary conditions have been replaced by perfectly matched layers. This allows us to separate the behavior of a single element from the behavior of the periodic lattice. The single element transmission roughly follows the transmission of the full structure with two major differences. First, the transmission through the periodic lattice is larger than through a single element, which can be explained through the coherent superposition of multiple elements. This will result in strongly focused scattering in the forward direction, as opposed to the larger angular distribution of a single element. The second difference between the curves is the appearance of sharp modes on the transmission of the full structure. These lines can all be attributed to lattice modes, and are calculated using $f_{2,0} = c_n \sqrt{f^2 + k^2 / \lambda}$ where $c_n$ can be the speed of light in either air or silicon and j and k are integers representing the mode order. The modes present in this figure go up to $f_{2,0}$ (29.85 THz) for the air side of the filter and $f_{6,3}$ (29.3 THz) for the silicon side. There are also local maxima in the single element transmission near 10.2 THz and 22.5 THz. An examination of the current patterns at the gold-silicon interface suggests that these are higher order modes.
modes of the cross element \((n=3\) and \(n=5\), respectively), but their highly oscillatory current distribution likely explains their weak coupling to the incident plane wave, as well as the absence of any other transmission bands.

To verify these simulated results, the fabricated samples were measured with THz-time domain spectroscopy using a two-color air plasma for generation\(^{23}\) and air biased coherent detection.\(^{24}\) This system does have a non-traditional Bessel-Gauss beam profile,\(^{25}\) but this beam profile is simply a superposition of Gaussian beams and is subsequently irrelevant to the filter performance. The optical pulse length used to generate the air plasma and THz beam was 35 fs, yielding an anticipated bandwidth of \(\sim 1/35\) fs \(= 28.6\) THz which is approximately that achieved in our reference measurements. Further details of the experimental system can be found elsewhere.\(^{26}\) The samples were also measured in a Fourier transform infrared spectrometer (FTIR) to examine their high frequency extinction up to 240 THz (1.25 \(\mu m/0.99\) eV).

An aggregate comparison between simulation and experiment for all samples is shown in Figure 3. The two plots compare \(f_0\) and \(\Delta f\) versus \(\sigma\) for both the single- and double-sided samples. Fits to the data were conducted using a power law and the simulated values in Table I. The resulting equations are \(f_0 = 8.22 \times \sigma^{-1.42} + 0.28; \Delta f_1 = 5.51 \times \sigma^{-1.56} + 0.22\); and \(\Delta f_2 = 3.16 \times \sigma^{-1.05} - 0.21\), where \(\Delta f_1\) is for the single-sided sample and \(\Delta f_2\) is for the double-sided. For fit details, see Ref. 27. Note that both the single- and double-sided samples share the same resonance frequency, because, due to the relative thickness of the HR-Si substrate, there is no coupling between these two layers and they can be treated independently at the band pass frequencies.\(^{28}\) The double-sided structures show a reduced \(\Delta f\) due to transmission through two filters, demonstrating that multiple filters can be stacked to achieve an even narrower bandwidth, as required. It is our hope that these design equations can be used to quickly fabricate bandpass filters for any frequency in this range. Simply calculate \(\sigma\) for the desired \(f_0\), use the geometric equations to determine \(L, W, P,\) and then calculate \(\Delta f_1\) and \(\Delta f_2\) for the subsequent filters. Since \(L, W,\) and \(P\) are linear with \(\sigma\), they also have a nonlinear relationship with frequency and the same scaling behavior as \(\sigma\). They decrease monotonically from \(L = 0.20 \times \lambda_0, W = 0.13 \times \lambda_0;\) and \(P = 0.28 \times \lambda_0\) for \(\sigma = 1\) to \(L = 0.13 \times \lambda_0, W = 0.08 \times \lambda_0;\) and \(P = 0.18 \times \lambda_0\) for \(\sigma = 6.25\), where \(\lambda_0\) is the free space wavelength at \(f_0\).

Metamaterials are well-known to be scale invariant, yet our scaling equations are clearly not linear with sample size. This scale invariance is broken by the constant value of \(\varepsilon\), which results in increased coupling in the trapped mode excitation with increasing \(\sigma\) and causes a red shift in \(f_0\). As a visual aid, Figure 3(a) has a line that is \(f_0\) of the \(\sigma = 1\) filter scaled linearly with \(\sigma\). The deviation of the results from this line demonstrates the aforementioned red shift vs \(\sigma\).

We can model this increased coupling by assuming that the capacitance of the metamaterial composite is dominated by the capacitive coupling between the cross element and the metal mesh filter. We begin by describing the filter as a resonant element, where \(f_0 \sim 1/\sqrt{LC}\) and \(L\) and \(C\) are the total inductance and capacitance of the metamaterial, respectively. Next, we assume that the capacitive coupling between the cross element and the metal mesh filter can be approximated as a parallel plate capacitor with capacitance \(C \sim \text{area/distance,}\) and this contribution dominates the total capacitance of the structure. Making this substitution for \(C,\) we see that \(f_0 \sim N/\sqrt{\varepsilon},\) where \(\varepsilon\) is the distance between the cross element and the metal filter, and every other dependency has been lumped into the unknown variable \(N.\) The scale invariance of Maxwell’s equations tell us that if we assume \(\varepsilon = 1.5 \times \sigma,\) then every dimension would scale linearly and the resonance frequency would match the linear approximation plotted in Figure 3(a). This means that \(f_0 \sim N/\sqrt{\varepsilon} \sim N \sim \sigma^{3/2}.\) If we instead hold \(\varepsilon\) constant, as we do in our metamaterial samples, we have \(f_0 \sim N/\varepsilon \sim N \sim \sigma^{3/2}.\) This yields an exponent of \(-1.5,\) which agrees closely with our fitted value of \(-1.42.\)

The scaling of \(\Delta f\) can be described in a similar manner. If we assume that the majority of the energy stored in the filter is in the electric field of the previously mentioned “capacitor,” we can use \(Q \sim 1/f_0RC\) for a capacitive element. Again using our substitutions for \(f_0\) and \(C,\) we have \(Q \sim 1/f_0C \sim 1/\sqrt{\varepsilon} \sim \sqrt{\varepsilon}\) which is constant. Since we also know that \(Q \sim f_0/\Delta f,\) a constant \(Q\) implies that \(f_0\) and \(\Delta f\) scale identically, and, therefore, \(\Delta f \sim \sigma^{3/2},\) which is again close to the fitted value of \(-1.56.\) While this simple argument ignores any changes due to fringing fields, surface capacitance,\(^{29}\) and inductance, the agreement with the fitted scaling equations suggests that this simple capacitive coupling argument captures the essence of the physics at play.

We have also examined \(\Delta f\) for transmission through up to six filters and have, for the sake of design convenience,
included the fitted equation for $\Delta f_{e}$ listed previously. However, we hasten to add that we do not attach any physical significance to the scaling behavior of this equation. This is because the changes in capacitive coupling strength due to constant $\varepsilon$ result in changes to the transmitted lineshape between the various $\sigma$ samples. When squared, cubed, etc., these different lineshapes all display reduced $\Delta f_{e}$ but not in a consistently meaningful way. As an example of this lineshape difference, an asymmetry can be seen in the $\sigma = 1$ pass band in Figure 4(a) which is due to a slight decoupling of the trapped mode excitation.

In Fig. 4, we demonstrate the broadband agreement between the experimental and simulated results. For clarity, only a subset of the samples is shown in this figure. In the inset of Fig. 4(a), we present the FTIR spectra for the $\sigma = 3.75$ sample, which goes from 10.4–240 THz. The relatively featureless transmission displayed is representative of all the samples. In particular, it is worth pointing out that the single-sided sample (blue) is slowly approaching the reference (black) with increasing frequency from $-29$ dB at 30 THz to $-23$ dB at 160 THz when the signal approaches the noise floor. Our simple geometric extinction argument, which generated the vertical dashed lines in Fig. 2, predicts a high frequency extinction of $-22.5$ dB. More generally, this simple calculation matches the data within a few dB for all samples.

The choice of constant $\varepsilon$ has an impact on both the high and low frequency behavior. While not shown here, the simulated peak transmission through a double-sided 0.23 THz filter ($\sigma = 20$) is only 0.4 (−8 dB). This decrease is understandable, given that $\varepsilon$ is almost three orders of magnitude smaller than the central wavelength (1.3 mm) at that frequency and the filter begins to behave as a continuous gold film. While this transmission decrease can be offset with a larger $\varepsilon$, this increases the bandwidth of the pass band and noticeably reduces the transmission extinction at high frequencies. This reduced extinction can be seen in the various $\sigma$ samples in Figure 4(b). As $\varepsilon$ decreases, the ratio of bare substrate to unit cell increases (which, due to our scaled samples, mimics increasing $\varepsilon$), and these samples, subsequently, have vastly increased transmission at 30 THz.

To create a filter with a frequency higher than 8.51 THz, a smaller value of $\varepsilon$ is required. For the $\sigma = 1$ (8.51 THz) filter, the geometry is completely limited by $\varepsilon$ and cannot be shrunk any further (for $\sigma = 1$, $W = 3 \times \varepsilon$). This could be counteracted with a smaller value of $\varepsilon$ using other fabrication methods, e.g., deep-UV photolithography or electron beam lithography with smaller achievable linewidths, but again, the design presented here was chosen for low cost, ease of fabrication, and widespread applicability.

Last, it is worth identifying the limits on the extinction range. The FTIR has shown high extinction up to 240 THz, but that is merely the limit of the measurement. The first practical limitation is the band gap of the HR-Si substrate at 271 THz (1.11 μm/1.12 eV). While the band gap would continue to extinguish any transmitted spectrum, the photoeexcitation of the substrate would also extinguish the desired pass band, defeating the purpose of the device. With a suitable substrate choice, such as a high band gap semiconductor or air, this limit could be pushed to even higher frequencies. On the low frequency side of the spectrum, the extinction is limited solely by the skin depth of the gold film.

In conclusion, we have shown that a metamaterial composite can have an ultra-broadband usable bandwidth that is suitable for virtually any THz source. We have constructed a series of bandpass filters that clearly demonstrate this concept, provided simple equations that can be used to construct filters at any frequency from 0.86–8.51 THz without need for...
simulation or design, and described the nature of the scaling laws in the equations. These filters may be fabricated on both sides of the HR-Si substrate for further bandwidth reduction, and multiple filters may be used to narrow the transmitted spectrum even further as required. It is our hope that this work will bring an easy to fabricate, functional THz component to the laboratory, and expand the reach of metamaterial-based THz components towards broadband functional components.

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27. The fits used the simulated data from Table I and the Matlab Curvefitting Toolbox using a power law $f = Ar^2 + C$. We have rounded to two decimal points in the text to match the precision of the values in Table I. The full results for $f_0$ are $A = 8.223$ (8.168, 8.278), $B = -1.424$ ($-1.449$, $-1.399$); $C = 0.2774$ (0.2191, 0.3357); $\Delta f_1$ are $A = 5.511$ (5.376, 5.645); $B = -1.557$ ($-1.661$, $-1.454$); $C = 0.2178$ (0.07851, 0.3571); and $\Delta f_2$ are $A = 3.161$ (2.972, 3.35); $B = -1.046$ ($-1.189$, $-0.9027$); $C = -0.2098$ ($-0.4184$, $-0.001059$), where the parantheses represent the 95% confidence bounds.