From mm-wave to THz: Scalable Filter Design for Ultra-low Cost Applications

W. J. Otter, F. Hu, J. Hazell and S. Lucyszyn

Centre for Terahertz Science and Engineering, Imperial College London

Optical and Semiconductor Devices Group, Electrical and Electronic Engineering, Imperial College London

Abstract:- This paper shows simulated and measured results of ultra-low cost metal mesh filters in the millimetre-wave and THz bands. It provides a broad overview of the filters currently available and their suitability for ultra-low cost applications. We demonstrate scalable conventional metal mesh filters on standard 525 µm fused silica substrates. In additional, trapped-mode excitation is used to improve out-of-band rejection at higher frequencies. The measured results show that these filters are scalable in the THz range using cost-effective micromachining manufacturing. This potentially opens up the possibility of using metal mesh filters for ultra-low cost applications.

I. INTRODUCTION

Metamaterials-based terahertz devices (e.g. sensors and filters), amplitude/phase and spatial modulators provide a method to control and manipulate THz waves [1]. A simple example of this is metal mesh filters [2-3], which have been widely used in applications such as astronomy and are commercially available from 0.1 to 30 THz. A limitation in self-supporting film designs is that at higher frequency the metal becomes electromagnetically thick, thus waveguide modes can exist within the structure [4]. Efforts to create thin metallic films on thin substrates or the film encased within polymers have been demonstrated [5]. However thin substrates are fragile and expensive and, encasing the film within a polymer increases the cost because of the extra fabrication processing steps.

We demonstrate experimentally that with careful design, standard fused silica wafers (525 µm thick and 100 mm in diameter) can be used with standard surface micromachining, to create high performance, low cost and scalable metal mesh filters. Moreover, we demonstrate higher performance filter designs that cannot be realised using self-supporting metallic structures.

II. DESIGN

Figure 1 illustrates a conventional metal mesh filter with its spatial design parameters: lattice constant G, width of the cross K, length of the cross L and metal thickness h [2]. It has been found that to tune the filter response these parameters have the following dominant affects; (i) increasing the length of the crosses will decrease the resonance frequency; (ii) increasing the lattice constant will decrease the upper -3 dB cut-off frequency and, hence, reduce the bandwidth; and (iii) increasing the width of the crosses will slightly decrease both the resonance frequency and bandwidth. Finally we keep metal as thin as possible, to avoid unwanted waveguide modes within the crosses.

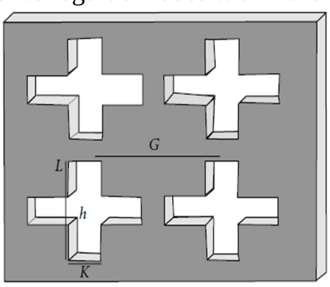

Figure 1: Cross shaped filter design parameters lattice constant (G), width of the cross (K) length of the cross (L), and metal thickness (h) [2].

The main challenge with the filter design is the thick substrate. If a high permittivity substrate is chosen, we will create a Fabry-Perot elaton, reducing the out-of-band rejection and causing interference with the mesh filter response. A second consideration is that the substrate will detune the filter as its centre wavelength $\lambda_R \rightarrow \lambda_{Ro}\sqrt{(n_1^2+n_2^2)/2}$, where $\lambda_{Ro}$is the filter's centre wavelength in free-space and n_1, n_2 are the refractive indices of the materials on either side of the mesh. This means with a substrate having $n_{1,2} > 1$ the filter is detuned to a longer wavelength.

Table 1 shows the optimised filter parameters to achieve resonances at 0.1 THz intervals over the 0.1 to 0.5 THz frequency band. Simulations show that our conventional metal mesh filters produce the expected filter responses at desired frequencies. However, out-of-band rejection for these cross-shaped filters is poor, as seen in Fig. 2.

Table 1: Optimized cross-shaped filter parameters

f_R (THz)	G (µm)	K (µm)	L (µm)
0.1	1150	100	975
0.2	680	50	423
0.3	440	30	293
0.4	360	20	210
0.5	290	15	160

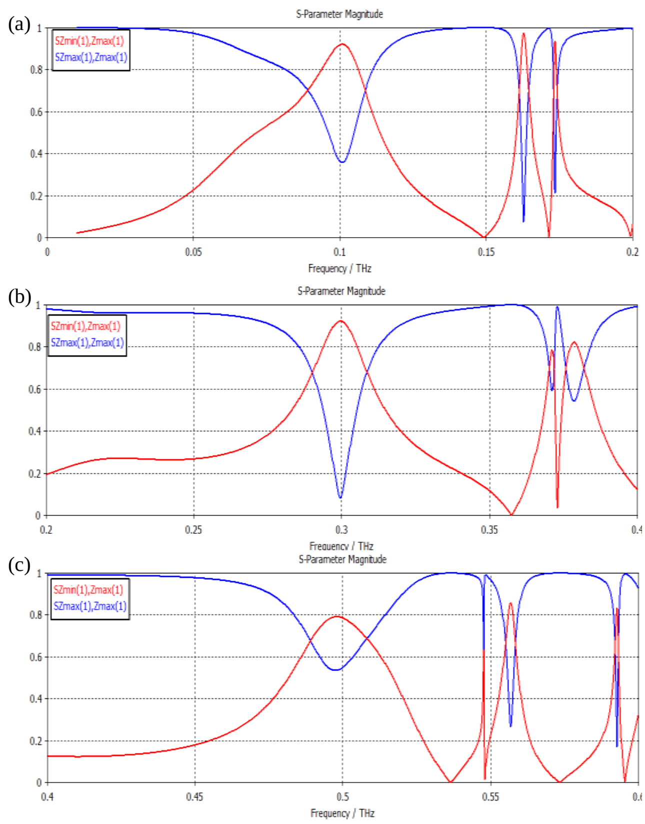

Figure 2: Simulated results of cross-shaped filters at (a) 0.1, (b) 0.3 and (c) 0.5 THz

A method of improving the out-of-band rejection is to add an inner cross, causing a trapped-mode excitation [6], which has the opposite surface current to the outer structure as shown in Fig. 3. Table 2 shows optimised parameters for two filter designs, at 0.1 and 0.3 THz, where K_2 and L_2 are associated wit the inner cross dimensions. The simulated performances are given in Fig. 4. Compared with the corresponding simulations with conventional cross-shaped filters, shown in Fig. 2, there is a greatly improved out-of-band performance.

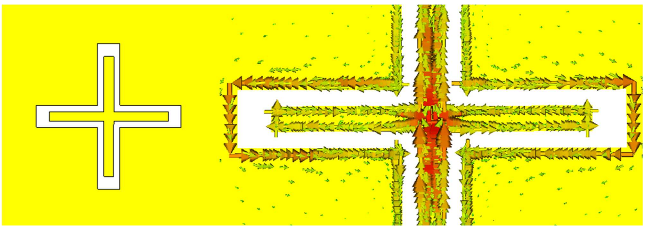

Figure 3: (left) Trapped-mode filter shape and (right) current distribution in the metal

Table 2: Optimized trapped-mode excitation filter parameters

f_R (THz)	*G* (μm)	*K* (μm)	K_2 (μm)	*L* (μm)	L_2 (μm)
0.1	978	92	51	744	540
0.3	365	36	16	234	193

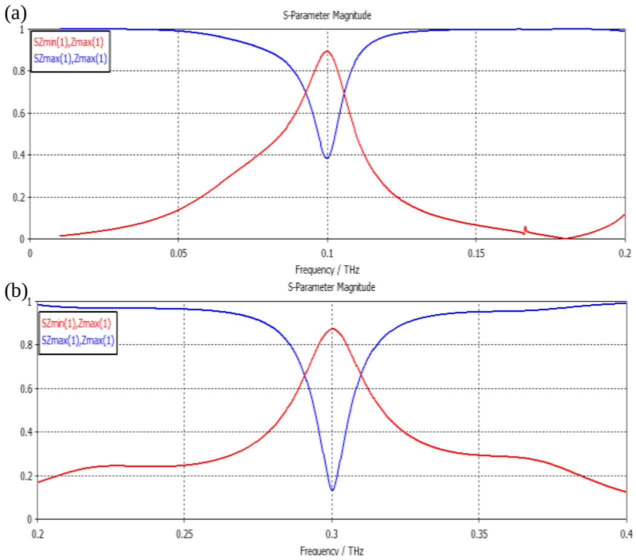

Figure 4: Simulated results for trapped-mode filters at (a) 0.1 and (b) 0.3 THz

III. FABRICATION

Figure 5 shows the fabrication steps for the filters. First, the substrate is sputter-coated with 35 nm of chrome, acting as a seed layer for the 150 nm gold layer. A 1 μm thick S1813 photoresist layer is spun on the wafer, soft baked and then exposed and developed using standard photolithographic techniques. The two metal layers are etched separately, using selective gold and chrome wet etchants, respectively. The photoresist is stripped using acetone and the sample is then cleaned with IPA. Microscope images of the fabricated filters are shown in Fig. 6.

IV. MEASURED RESULTS

The filters were measured using our turnkey TeraView 3000 terahertz time-domain spectroscopy (THz-TDS) system. The results are as shown in Fig. 7. The measured 0.4 THz conventional cross-shaped filter design shows a pass band at 0.4 THz; a second mode at 0.5 THz is observed, showing a poor out-of-band rejection. The 0.3 THz trapped-mode design shows better out-of-band rejection, as well as an increase in transmission.

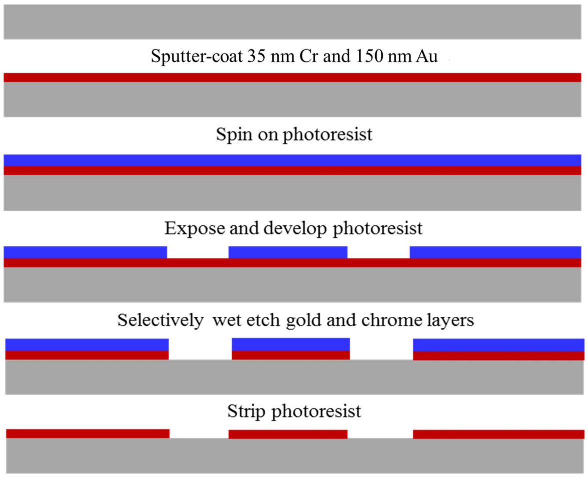

Figure 5: Surface micromachined processing steps

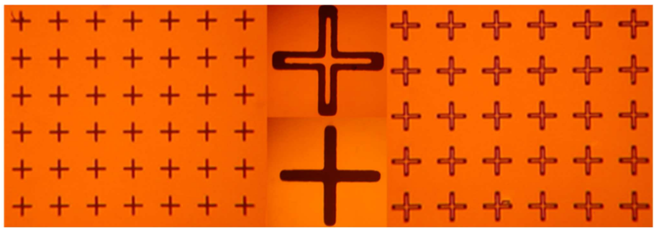

Figure 6: Microscope images of both (left) cross-shaped and (right) trapped-mode THz metal mesh filters

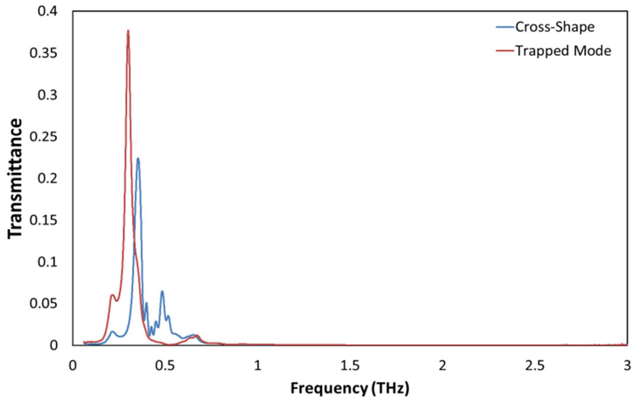

Figure 7: Measurements of 0.4 THz cross-shaped and 0.3 THz trapped-mode filters

V. CONCLUSION

We have shown the design, simulation and measurements for conventional cross-shaped and improved trapped-mode scalable ultra-thin metallic film THz filters on electrically thick substrates. This shows the possibility of employing metal mesh filters on thick substrates for low-cost THz applications.

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