

Low-cost bandpass filter for terahertz applications

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Abstract Compared to the visible and infrared regions of the electromagnetic spectrum, development of optical components in the terahertz region has progressed slowly even though the feature size of structures makes many of them easily attainable by many conventional manufacturing techniques. Of these, the performance of components with machined metal surfaces, such as filters, typically has suffered from the errors and inconsistencies in the manufacturing which has led many to manufacture these using more expensive deposition and processing tools. Here we show that by using a novel, high power Yb:doped pulsed nanosecond fiber laser system with exceptional beam quality, aluminum metal surfaces can be machined with high precision leading to a high quality band pass filter working in the terahertz frequency range. The filter was laser machined on a 0.05 mm thick aluminum substrate over a 1 cm² area where the unit cell in the pattern had an equilateral triangular geometry in which the base length between the holes and the diameters were machined with better than 4 % accuracy. The produced structures are modeled by utilizing the obtained structural parameters in a waveguide configuration and then characterized by the existing home-built time-domain terahertz spectrometers in our laboratories. The results show a near 100 % power transmission at the desired terahertz frequency range which suggests that these manufacturing techniques can be used to produce low-cost THz filters.

Keywords THz · TDS · Terahertz · Fiber laser · Filter

1 Introduction

With the rapid development of technologies in the terahertz region there is a need to develop cost-effective optical components to be implemented in such systems. For applications which require frequency selectivity, such as reducing radiation background levels for imaging purposes or filtering noise for signal processing various types of filter structures can be utilized

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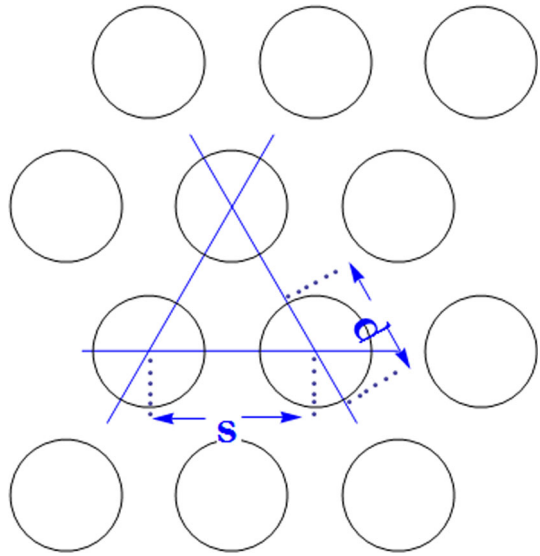
(Chen et al. 2007; Melo et al. 2008). Typically, these structures or devices perform the frequency filtering by modifying the propagation of the input wave with respect to changing structural parameters of the device itself. Fortunately, for sub-millimeter wave to low frequency terahertz radiation applications (<1 THz) the feature sizes of these structural changes are on the order of sub-mm to mm making their manufacture attainable by various fabrication technologies. Previous studies have utilized computer controlled milling machines or even material deposition technologies such as chemical vapor deposition or thermal evaporation to produce such filters (Gallant et al. 2007; Haupt et al. 2004; Winnewisser et al. 1998). Recently, there has been much progress in the development of lasers for machining metal surfaces. Of the recent advances, the use of fiber lasers are becoming the industry standard due to their exceptional beam qualities even at high average powers (Richardson et al. 2010). Furthermore, recent research has shown that precision machining on better than micron scales can be achieved with ultrashort pulses thereby negating any thermal affects that can arise from continuous wave beams (Murakami et al. 2009). In a recent study, fine patterns on metal surfaces were created using varying pulse length and varying repetition rate picosecond pulsed Yb:doped fiber lasers. The results showed that while processing times increased, finer patterns were created with pulses whose time scales were on the order of nanosecond or else with high repetition rates of more than 1 kHz (Hendow and Shakir 2010).

Here we use a high-power nanosecond pulsed Yb:doped fiber laser to create the filters by laser ablation of aluminum substrates which allow us to reduce the cost of manufacture of these terahertz components. The transmission was modeled using the waveguide based transmission geometry of the pattern. After the filter was manufactured it was tested using a home-built terahertz time-domain spectrometer driven by a Ti:Al₂O₃ oscillator laser.

2 Background

Lasers are excellent tools to modify materials such as metals, ceramics, plastics and semiconductors. It has been shown that the use of short-pulsed lasers has greatly increased precision and resolution of such modifications in the last two decades (Breitling et al. 2004). The best precision for structuring metals is obtained with femtosecond pulses as compared to picosecond and nanosecond pulses (Cheng et al. 2013). Very high peak powers directly evaporate the material so that molten residue is not observed. On the other hand, nanosecond pulses can give better results than picosecond pulses in terms of depth and ablation. As such, the most common method for processing thin sheets of metals up to ~ 1 mm in thickness are nanosecond pulsed lasers due to their advanced development in overall system design as compared to shorter pulsed techniques. For nano-pulsed metal processing, both vapor and liquid phases of material are removed because nanosecond pulses are long enough for thermal effects to propagate into the material. Here, the vaporized material removes liquid material creating a recoil pressure (Chichkov et al. 1996) Most commonly used nano-pulsed laser for these purposes have been Q-switched Nd:YAG or similar diode pumped solid state lasers. Now, fiber lasers are becoming even more popular due to several advantages such as simple and stable operation, low cost and high beam quality. Their ease of use and variable output parameters such as repetition rate allows these lasers to be also used in finesse applications such as marking, texturing (Erdogan et al. 2011), and micromachining (O'Neill and Li 2009). In addition, ultrafast mode-locked fiber lasers are now being also used in THz spectroscopy systems due to their compactness and stable performance (Keskin et al. 2014). Typical parameters used in nanosecond pulsed operation with Yb:doped fiber lasers are 10–100 ns pulse duration, 10–50 W of average power and repetition rates in the range of 20–500 kHz. The long

Fig. 1 Schematic representation of the filter with circular openings of diameter d , arranged in equilateral triangular lattice with element spacing s



pulse duration with respect to picosecond pulses results in more efficient material removal, while minimizing heat effects due to the short enough pulse durations, relative to continuous wave lasers. Due to the thickness of the substrate and material, the parameters used for the processing of the filter were typical for these laser systems. However, the difference as can be seen in the processed filter lies in the exceptional beam quality of the Yb:doped fiber laser that was used, an M^2 value better than 1.2.

The structures were manufactured by laser ablating a 0.05 mm thick aluminum substrate using a 1,064 nm center wavelength, 70 ns pulse width, 70 kHz repetition rate, 25 kW peak power Yb:doped fiber laser (Nanomark 20 W, Fiberlast Inc., Ankara, Turkey). It is important to note that the method used here produced a filter with exceptional quality for a fraction of the cost of other methods previously used in similar studies. For example compared with producing a filter on a PCB board, which is another low-cost method used for obtaining filters in this frequency range, we find out that the cost of manufacturing of a single filter is an order of magnitude greater than the one presented here. Manufacturing costs become comparable only if more than 100 filters are produced. Even then, the precision in the PCB THz filter production can be on the order of 10% of the intended feature size, which results in a poor filter performance. As is demonstrated here the laser spot size of about $30 \mu\text{m}$ at the focus of the beam was accurate enough to produce the desired filter pattern on the aluminum substrate. The filter structure was patterned in one single process. The pattern that was used for the laser machining is based on a similar pattern as was suggested by [Winnewisser et al. \(1998\)](#). The filter consists of 270 circular openings of diameter arranged in equilateral triangular lattice (see Fig. 1). The diameters of circular openings and element spacing are measured by using an image detection algorithm on the micrograph given in Fig. 2a. Mean diameter, d , is found to be $571 \mu\text{m}$ with standard deviation of $14 \mu\text{m}$ and the mean element spacing, s , is found to be $793 \mu\text{m}$ with standard deviation of $20 \mu\text{m}$.

Transmission characteristics of a conducting perforated plate are calculated by [Chen \(1973\)](#). The cutoff frequency ν_c is given as,

$$\text{for TM modes: } \nu_c = p_{nm} \frac{c}{\pi d} \quad (1)$$

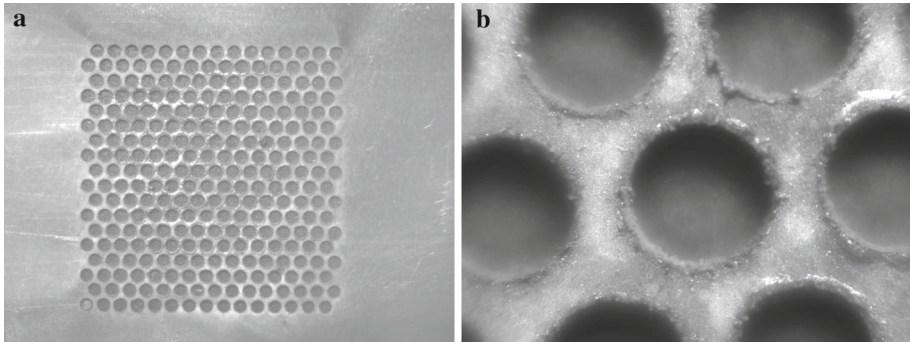


Fig. 2 **a** Laser processed THz filter showing pattern over 1 cm² area, **b** close-up view of the triangular pattern showing the regular shapes of the pattern

$$\text{for TE modes: } v_c = p'_{nm} \frac{c}{\pi d} \tag{2}$$

where p_{nm} (p'_{nm}) is the m -th root of $J_n(x)$ ($\frac{d}{dx} J_n(x)$) (i.e. Bessel function of the 1st kind and its derivative). The region below the cutoff frequency, $v < v_c$, is the stop-band where the wave is attenuated over a characteristic length of the waveguide, $\alpha^{-1} = \frac{2\pi}{c} \sqrt{v_c^2 - v^2}$. Whereas above the cutoff frequency, $v > v_c$, the wave can pass through the waveguide without loss.

The reflection and the transmission coefficients are derived for the case of normal incidence as (Chen 1973):

$$R = \frac{1}{1 - i[A + B \tanh(\beta l)]} + \frac{1}{1 - i[A + B \coth(\beta l)]} - 1 \tag{3}$$

$$T = \frac{1}{1 - i[A + B \tanh(\beta l)]} - \frac{1}{1 - i[A + B \coth(\beta l)]} \tag{4}$$

where A and B depend on the geometry of the filter. The power transmittance can be calculated by,

$$T_p = T^* T \tag{5}$$

For circular openings with equilateral triangular lattice, two functions are given as (Chen 1973):

$$A = 12 \left(\frac{4}{3} \left(\frac{\lambda}{s} \right)^2 - 1 \right)^{1/2} \left[\frac{J'_1 \left(\frac{2\pi d}{\sqrt{3} s} \right)}{1 - \left(\frac{2\pi d}{1.841 \sqrt{3} s} \right)^2} \right]^2 - \frac{12}{\left(\frac{4}{3} \left(\frac{\lambda}{s} \right)^2 - 1 \right)^{1/2}} \left[\frac{J_1 \left(\frac{2\pi d}{\sqrt{3} s} \right)}{\frac{2\pi d}{\sqrt{3} s}} \right]^2 \tag{6}$$

$$B = 1.32 \left(\frac{s}{d} \right)^2 \left(\left(\frac{0.586\lambda}{d} \right)^2 - 1 \right)^{1/2} \tag{7}$$

For TE₁₁ mode β is given as,

$$\beta = \frac{2\pi v}{c} \sqrt{1 - \left(\frac{p_{11}c}{\pi d v} \right)^2} = \frac{2\pi}{\lambda} \sqrt{1 - \left(\frac{0.586\lambda}{d} \right)^2} \tag{8}$$

The diffraction limit of the plate is found by noting that at normal incidence diffraction into the first lobe appears for frequencies above

$$v_{\text{diff}} = \frac{1.1547c}{s} \tag{9}$$

3 THz time domain spectroscopy (THz-TDS) system

In order to measure the transmissive properties of the filter, a home built THz-TDS system was used as shown in Fig. 3. A Ti:Al₂O₃ mode-lock laser operating at a center wavelength of 800 nm, a pulse duration of 16 fs and repetition rate of 75 MHz with an average power of 20 mW is used to drive the system. A beam splitter with a 95/5 % of transmission ratio splits the incoming beam into the two optical arms of the spectrometer. In the generation arm, terahertz generation is performed using a multi-dipole photoconductive antenna (iPCA-21-05-1000-800-h, BATOP 2014GmbH, Jena, Germany). The polarization of the generated THz beam was perpendicular to the plane (s-polarization). The THz radiation is coupled to the system via hyper hemispherical silicon substrate lens which is attached to the substrate of the antenna. Generated THz rays in antenna are guided through the system using two off-axis parabolic mirrors and two lenses. The two lenses are similar (TPX lens, D=50 mm, F#2) and are used to focus the THz beam onto the sample with a spot diameter of about 5 mm. Afterwards the THz beam is propagated colinearly with the laser beam from the detection arm through a 2 mm thick (110) ZnTe crystal, where after the electric field of the THz pulse is measured using electro-optic detection method through a balanced photodiode. Phase-sensitive detection is used by a lock-in amplifier which is referenced to an applied AC bias

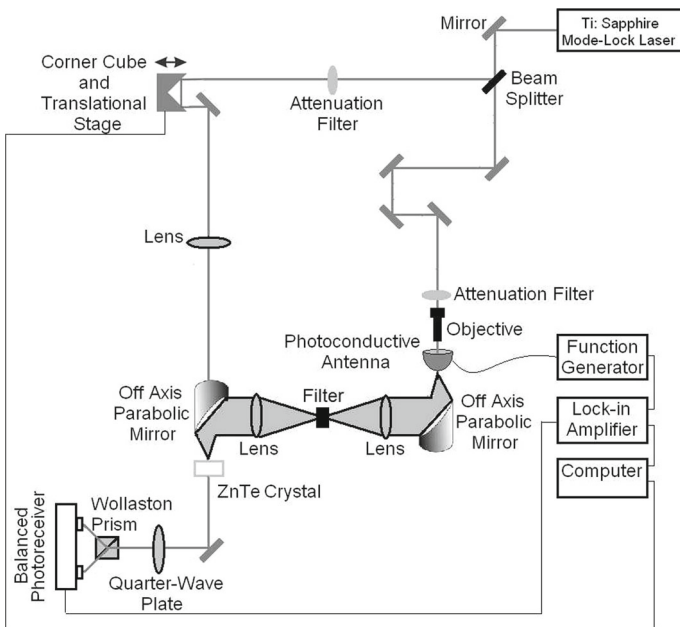


Fig. 3 THz-TDS system driven by Ti:sapphire mode-lock laser. A photoconductive antenna is used as THz source

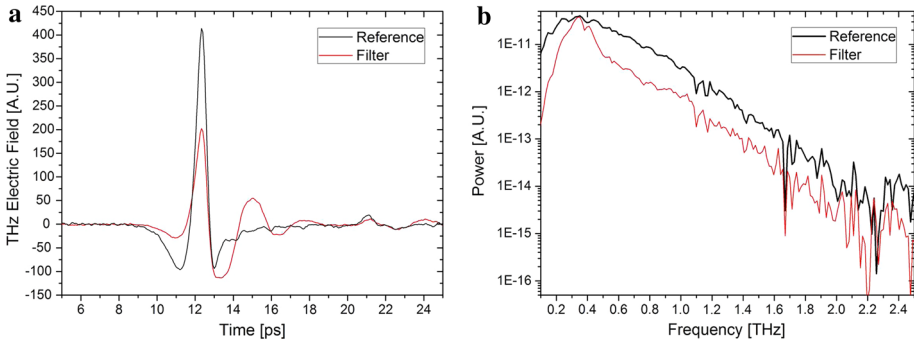


Fig. 4 **a** Measured THz signal profile of reference and filter, **b** calculated power spectrum of reference signal and filter measurements using respective THz signal profiles

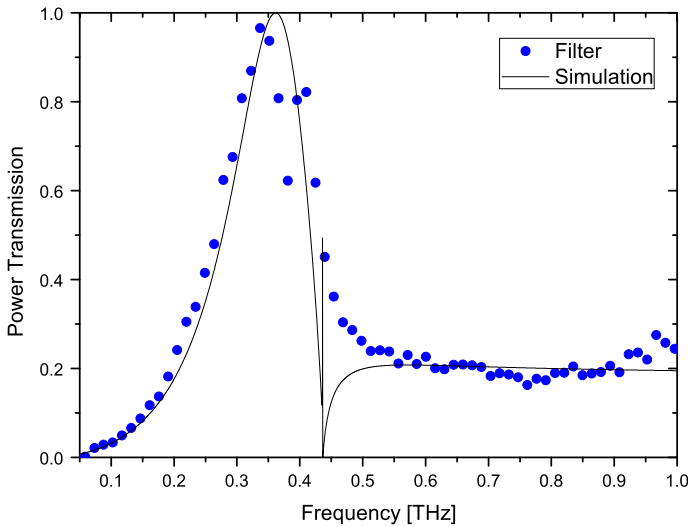


Fig. 5 Power transmission of THz filter together with simulation result. The filter parameters are $s = 793 \mu\text{m}$, $d = 571 \mu\text{m}$, $l = 50 \mu\text{m}$, $\nu_c = 0.307 \text{ THz}$, $\nu_{\text{diff}} = 0.435 \text{ THz}$

on the photoconductive antenna. The data is recorded with the aid of a PC and data acquisition software.

4 Results

The measurements were performed after purging the system with nitrogen to a relative humidity level of 8 %. The time-domain transmission data were collected with and without the filter (see Fig. 4a). Afterwards the data is analysed by applying a Fourier transform to obtain the frequency response of the filter (see Fig. 4b). Using frequency domain data the power transmittance of the filter is obtained. Theoretical power transmittance is calculated from Eq. (5) using parameters given in Fig. 5. Also measured and simulated power transmission is shown in Fig. 5.

5 Conclusions

Terahertz applications are developing rapidly thanks to an ever increasing interest in fields such as communications and imaging. To ensure unhindered progress technologies need to be developed which not only offer high quality in implementation but also are cost-effective solutions. In this study, theoretical background and fabrication of a low-cost bandpass filter for terahertz frequencies are presented. The results show that by altering the filter feature size parameters, it can be possible to produce filters for different regimes with near 100% transmission at the desired frequency. The measurements when compared with the simulation show that a near perfect transmission can be achieved at certain frequencies. This suggests that the filter that was produced with a high degree of precision. This is also confirmed by the micrograph measurements where the differences in feature sizes varied by <0.02 mm ($<4\%$ across the pattern). This is well within the spot size of the laser beam which suggests that finer focuses can even lead to better tolerances, which in turn will allow smaller deviation in element spacing and diameters. This will result in more precise determination of cutoff frequency, ν_c , and diffraction limit, ν_{diff} , during the production progress. Overall, these results suggest that pulsed fiber laser technologies offer great potential towards development of structured surfaces for the terahertz frequency range.

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