Enhanced THz transmission apertures through sub-wavelength annular apertures

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ABSTRACT

We report on the development of a surface micromachined process for the fabrication of coaxial apertures surrounded by periodic grooves. The process uses a combination of copper electroforming and the negative epoxy based resist, SU8, as a thin flexible substrate. The device dimensions are suitable for the implementation of filters at THz frequencies, and measurements show a pass band centred around 1.5 THz. These devices could form the basis of the next generation of THz biosensors.

Keywords: THz, sub-wavelength apertures, coaxial

1. INTRODUCTION

The THz gap (300 GHz to 10 THz) forms the interface between microwaves and the near infrared (see Fig. 1). Until recently it has been relatively unexplored, but considerable advances have now been made in the effective generation and detection of broadband THz signals [1]. The fundamental advantage over existing techniques, such as X-ray analysis, is the ability of THz to penetrate through materials, such as clothing, whilst simultaneously providing detailed spectroscopic information. These spectroscopic signatures can be used, for example, to identify concealed explosives [2].

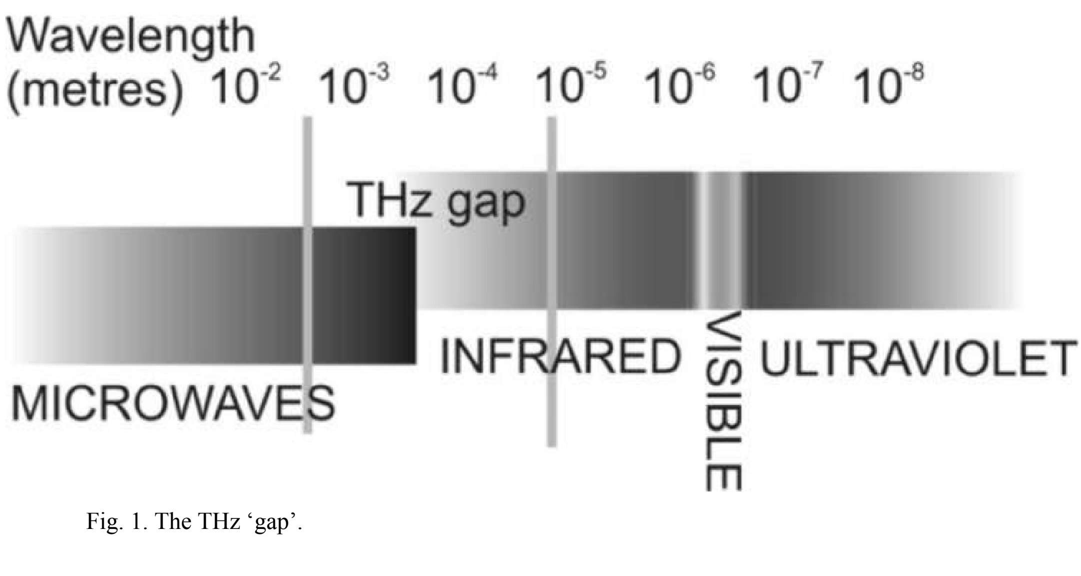

Fig. 1. The THz 'gap'.

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THz based imaging systems are now becoming commercially available through companies such as Teraview [3]. These systems have many applications in medical imaging, security and biotechnology. In particular, pulsed systems provide depth profile information alongside the spectroscopic data.

THz microscopes are also being developed [4], but are still in their infancy. These have the potential to further enhance the understanding of the fundamental properties of living cells, polymers and semiconductor devices. However, in order to fully exploit this technology it is imperative that new types of lenses and filters are developed for THz operation. The fundamental aim of the THz microscope is to enable the analysis of materials which are often physically smaller than the incident wavelength. The new elements will need to provide a route to sub-wavelength resolution.

2. SURFACE PLASMON BASED METAMATERIALS

Metamaterials have specifically engineered properties which may be unavailable in nature, such as a negative refractive index for perfect lenses [5] or specific transmission properties for filters [6]. Furthermore, additional problems such as the high attenuation coefficient of water at THz frequencies have the potential to be addressed through the propagation mechanisms of these new materials. This could then lead to a new ability to study samples with a high water content.

In 1998, Ebbesen et al [7] reported the enhanced transmission of light through sub-wavelength apertures in an optically opaque metallic film. The apertures were arranged in a periodic 2D array. The enhanced transmission, which can be several orders of magnitude above classical predictions, is frequency specific and therefore well suited to filter type applications. Fig. 2 shows a periodic array of holes fabricated using bulk micromachined silicon which is suitable for THz operation.

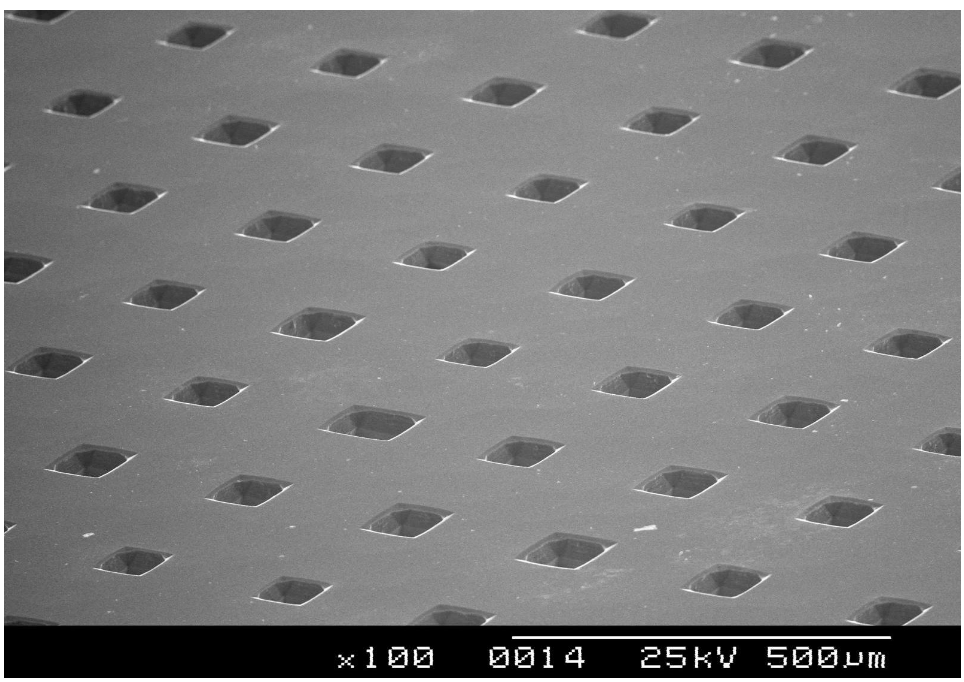

Fig. 2. Bulk micromachined hole array for THz filtering applications.

Subsequently, numerous papers have been published both experimentally and theoretically on this phenomenon, and it is now widely accepted that the enhanced transmission is caused by surface plasmon effects [8].

Surface plasmon polaritons (SPPs) are generated for specific frequencies of incident radiation. These can be formed on the incident face, from where they tunnel through the apertures along the surface and can be reemitted as radiation on the exit face [9]. However, periodicity is required for the effective formation of SPPs. The periodicity can be achieved through 2D arrays of apertures or single apertures surrounded by grooves [10]. A route to further enhancement was proposed by Baida *et al* [10]. This uses apertures with a central conductor, forming a coaxial type structure. The coaxial structure itself can only support particular frequencies. For microwave operation, Caglayan *et al* [11] demonstrated that this can be coupled with SPP based effects through the inclusion of periodic, concentric grooves.

In general it can be shown that the periodicity of apertures or grooves equates approximately to a resonant excitation wavelength. Therefore, for optical excitation, nanometre scale processing techniques such as e-beam writing, focused ion beam (FIB) etching or nanoimprint lithography are required. For microwave devices, conventional printed circuit board (PCB) millimetre scale techniques can be used. At THz wavelengths, (1 THz = 300μm) micromachining techniques are ideally suited.

Surface micromachining uses conventional integrated circuit techniques such as thin film deposition, photolithography and electroplating to produce three dimensional structures layer–by–layer. Fig. 3 shows an example of a surface micromachined device. Electroformed copper has been used to form a sub-wavelength slit and is surrounded by periodic grooves. This is a free space example where the incident radiation can pass directly through the slit without substrate associated attenuation and reflections.

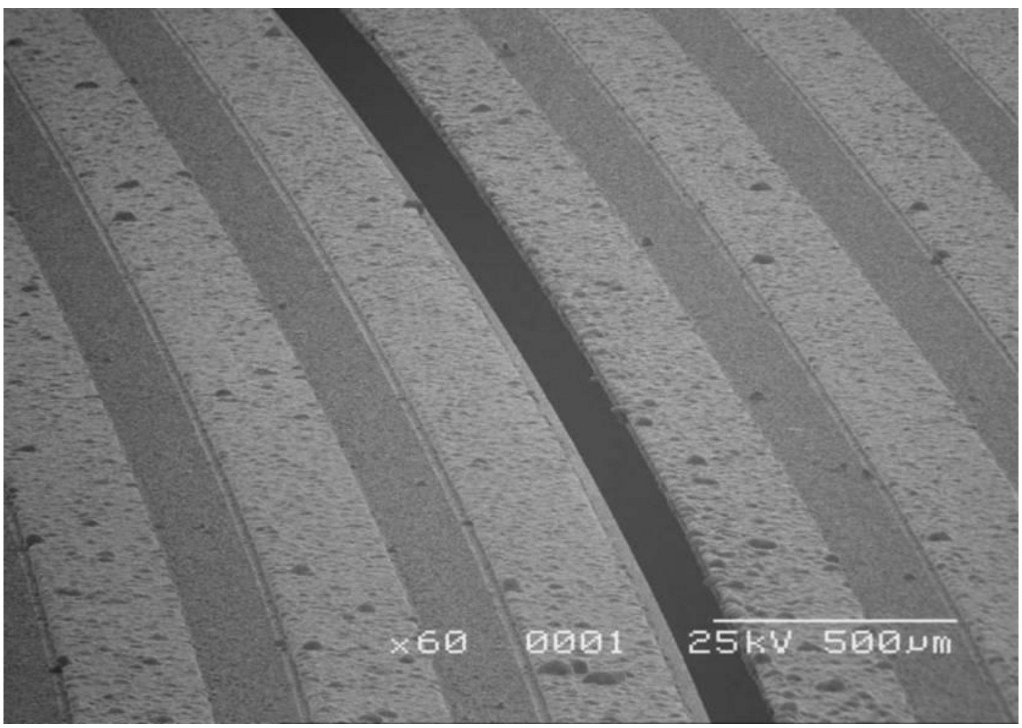

Fig. 3. Surface micromachined slit surrounded by copper with periodic grooves.

However, the structure presented in this paper is a coaxial aperture surrounded by periodic concentric grooves (see Fig. 4). The central electrode of the coax needs to be held in place. This is achieved using copper electroforming on a thin SU8 membrane and, to the best of our knowledge, is the first implementation for THz applications.

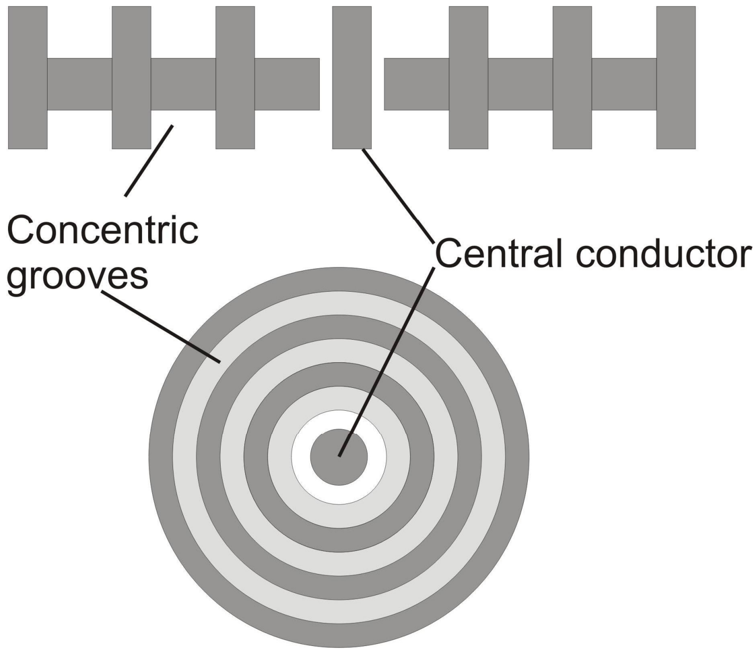

Fig. 4. Coaxial apertures surrounded by periodic grooves.

The transmission characteristics of surface plasmon based structures are highly sensitive to any materials on their output face [13]. However, in order to exploit, for example, the hole arrays as sensors then either a large area of the output face or many holes need to be filled with the sample under test. The coaxial aperture is interesting because only a single application of a small volume of material is required. The device demonstrated in this work could form the basis for such a sensor for biological analysis [14].

3. FABRICATION

Complete free space operation of the coaxial structures (as in the previous section) is not possible since the central conductor needs to be supported. However, even low loss THz transparent substrates such as quartz and high resistivity silicon introduce additional, unwanted, reflected pulses into the THz time domain signal. As an alternative we have chosen the negative epoxy-based resist SU8-10, deposited to a thickness of 20 μm, as a supporting substrate for the central conductor. Such a thin substrate minimises the effects of reflections and absorption.

Initial trials fabricated the structures using SU8 combined with thick gold electroforming on a silicon wafer. The wafer was etched using a XeF_2 dry etch. However, due to the high associated costs and commercial considerations this has been superseded by the copper-based process flow shown in Fig. 5.

The silicon substrate acts a mechanical support throughout the processing steps. First, S1813 photoresist is deposited onto the wafer, soft baked at 95 ˚C (2 mins), hard baked at 125 ˚C for (5 mins) and then coated with 650 Å of evaporated copper. This is then electroplated with a further 2 μm of copper in order to ensure stability of the layer throughout subsequent thermal processing. This has the added advantage of providing a relatively thick low resistance seed for the electroplating. The concentric ring structures have been found to be highly susceptible to electroforming current density issues such as preferential plating for the outer ring and relatively poor plating in the central rings.

AZ4562 resist is spun to a thickness of 20 μm and copper is electroformed to define the first set of grooves and the central conductor. The AZ4562 is removed and replaced with 20 μm thick SU8-10. This process order ensures that the central conductor is essentially glued to the SU8.

A thin Cr/Cu seed is then evaporated onto the wafer. It is important to ensure that this metal effectively bridges the electroplated metal rings to the SU8. If this does not occur then the next layer of structural copper does not electroplate onto the SU8 surfaces and at the final etch back stages these become cleared therefore rendering the device inoperable. This combined with the preferential plating issues presents an important yield issue.

AZ4562 is used to cover the coaxial gap and the copper is electroformed over the rest of the wafer to a thickness of 14 μm. This layer provides the main structural integrity to the device. Finally, the second set of grooves is defined by further copper electroforming to a thickness of 20 μm.

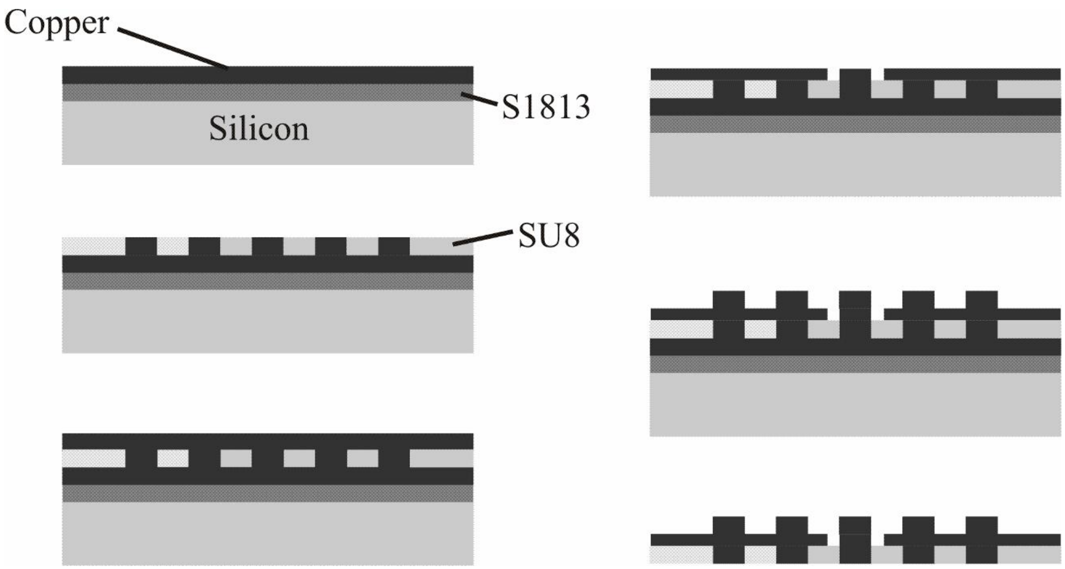

Fig. 5. Fabrication flow for the coaxial apertures surrounded by periodic grooves.

After fabrication, the entire Cu/SU8 membrane can be peeled away from the Si/S1813 substrate. The remaining Cu/Cr seeds are then wet etched away to reveal bare SU8 at the coaxial gap. A series of completed devices is shown in Fig. 6.

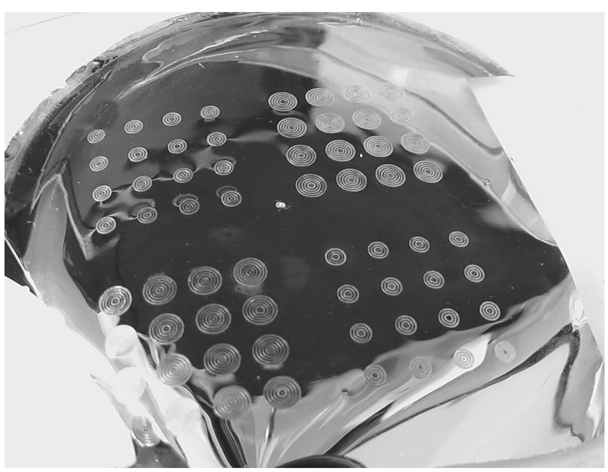

Fig. 6. Fabricated annular devices on a thin and flexible SU8 substrate.

4. THZ TESTING

A broadband THz – TDS (time domain spectroscopy) system is used to measure the relative transmission of the filters. This is shown in Fig. 7. The available bandwidth of the system is approximately 3 THz. The spot size can typically be focused to less than 1 mm diameter.

The Ti:sapphire laser produces a 600 mW pulse of 20 fs duration with a repetition rate of 76 MHz. This is separated into a THz generating and a gating beam with a 70:30 beam splitter. The generating beam is focused onto an LT-GaAs photoconductive strip-line emitter which is dc biased to 250V. Parabolic mirrors are used to focus the THz signal onto the sample.

The gating and the THz beam are focused onto a 1 mm thick ZnTe electrooptic crystal. This, in conjunction with a balanced detector is use to detect the transmitted THz [1]. A delay line on the generation signal allows the electric field of the THz pulse to be scanned in the time domain. A Fast Fourier Transform (FFT) is then used to obtain a frequency spectrum.

For relative transmission measurements, the sample scan is divided by a free space scan in the frequency domain. This effectively deconvolves any reflected signals associated with the measurement setup. In this paper, the samples are placed perpendicularly to the incident THz beam.

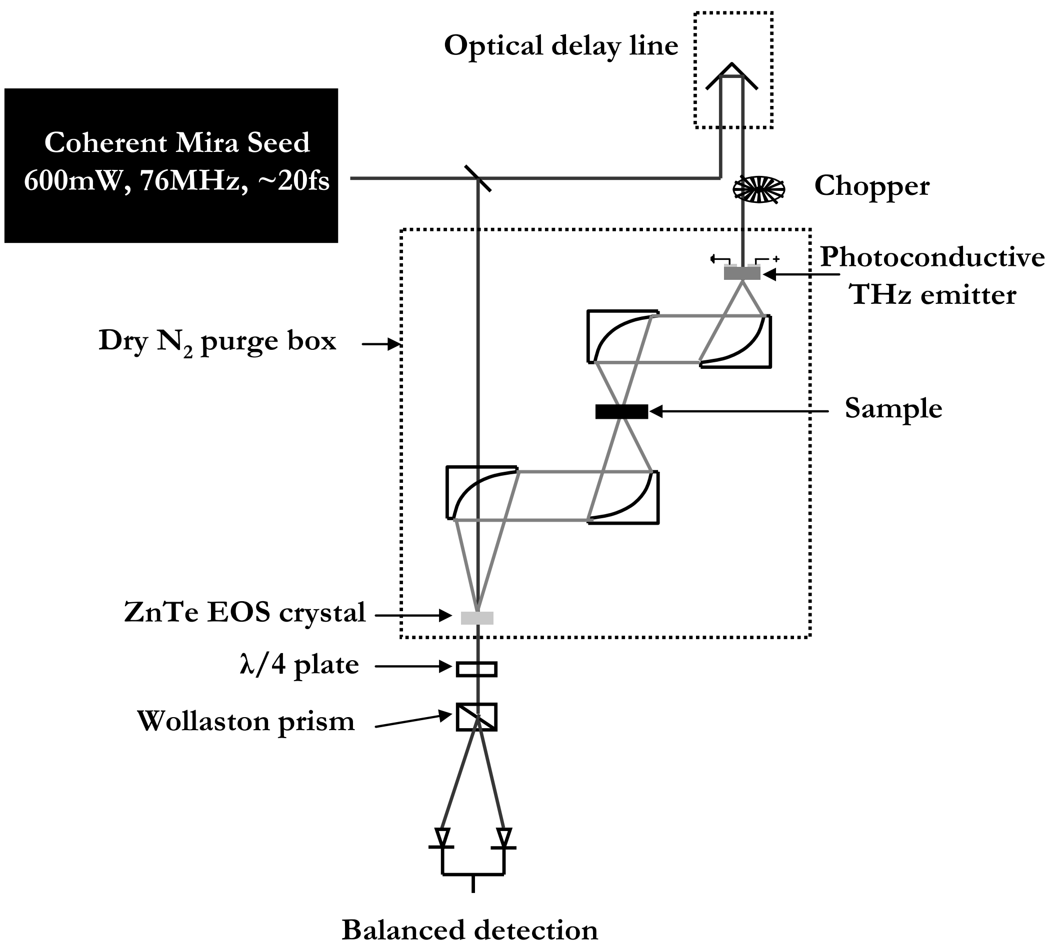

Fig. 7. A schematic of the broadband THz – Time Domain Spectroscopy (TDS) system.

The devices shown in Fig. 6 were fabricated with two concentric grooves (200μm period). The coaxial waveguide in theory should support a propagating mode in the region of 1.4 THz. This has a central copper diameter of 120 μm in an aperture with a diameter of 160 μm.

Fig. 8 shows the relative transmission characteristic for the coaxial aperture both with and without concentric grooves. Up to a 12 fold enhancement is observed with the inclusion of the grooves. The peak transmission at the coupled resonance is 16%.

Further work is being undertaken to optimise the resonant peak. Agrawal *et al* have reported that the SPP enhancement increases with deeper grooves [15] on bare aperture structures. The copper process flow can be adapted to allow for this. However, this is not a trivial change because on the output face it would require the use of thicker SU8 which would therefore increase the substrate associated attenuation. However, as it stands, this result represents the first reported demonstration of a coaxial aperture with concentric periodic grooves functioning in the THz region.

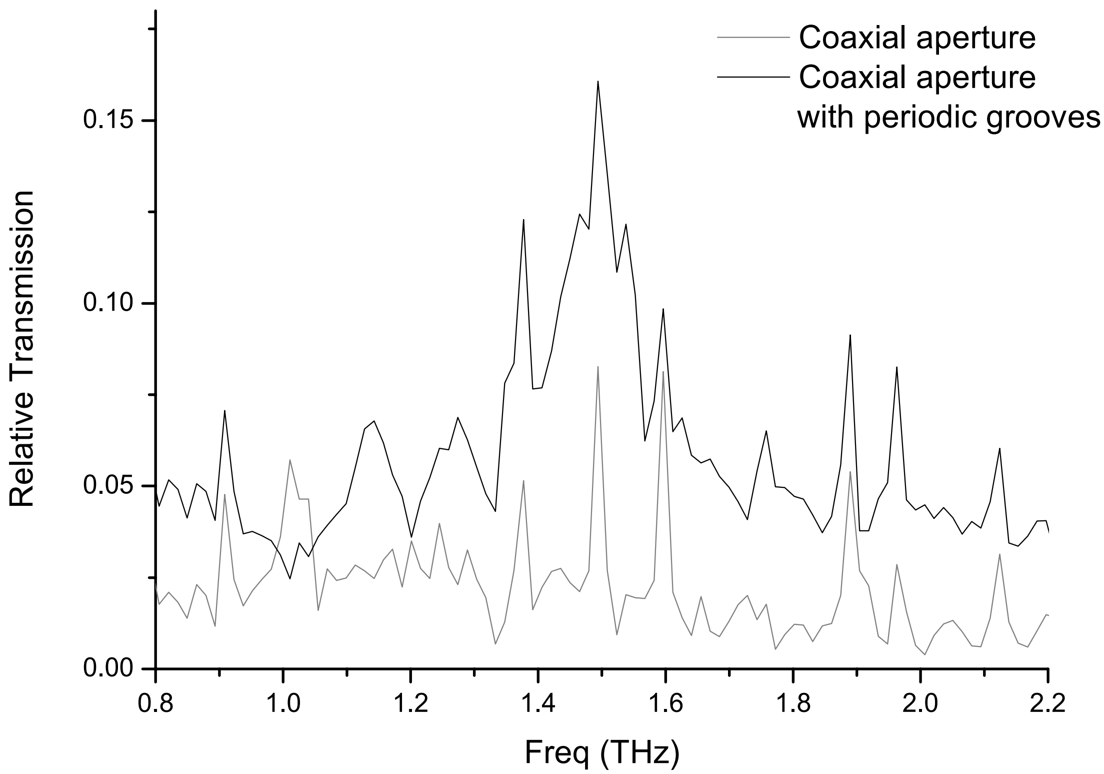

Fig. 8. Relative transmission of a bare coaxial aperture and a coaxial aperture surrounded by concentric grooves.

In addition to the further optimisation of the devices, it is also anticipated that they will be used for biosensing type applications where only a small sample volume is available to be tested. Unlike the equivalent structures at, for example, microwave or near infrared, the dimensions of the grooves and coax are well suited for this particular application and microlitre dispensing.

The surface micromachined process presented here is directly applicable to a range of artificial structures suitable for THz operation. In summary, it enables the fabrication of clear apertures surrounded by periodic grooves either in free space (where coax is not required) such as in Fig. 3, or with a thin, flexible, polymer substrate on the exit face for coaxial devices.

5. CONCLUSIONS

A surface micromachined copper electroplated process has been developed which enables the fabrication of coaxial apertures surrounded by concentric grooves. We have demonstrated that this structure can achieve up to 12 fold enhancement when compared to a bare coaxial aperture of the same dimensions. Further work is underway to optimise the performance of the structure which could eventually form the basis of a highly sensitive THz biosensor for microlitre bioanalysis.

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