A Frequency Selective Surface for Harmonic Suppression in THz-Multipliers

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Abstract—A quasi-optical filter for harmonic suppression in THz multipliers with a pass-band at 300 GHz and a stop-band at 450 GHz was developed. The filter consists of a 2-dimensional slot array, and is made from microstructured aluminium on an electrically thick, high-resistivity silicon substrate. The filter therefore have a very good mechanical stability and can be manufactured by using reliable processes available from the semiconductor industries. The design of the filter was based on the MoM/BI-RME method. The frequency response of the filter was optimized for a plane wave with oblique incidence angle and it was shown that fine-tuning of the stop-band can be accomplished by small changes of that angle. Measurements relying on THz-time-domain spectroscopy as well as CW-measurements show an insertion loss smaller than 1.6 dB at 300 GHz and a stop-band attenuation larger than 20 dB at 450 GHz.

Index Terms—Filter-Design, Frequency-Selective Surface, Quasi-Optics, THz-Technology.

I. INTRODUCTION

In the course of increasing interest in the millimeter and sub-millimeter wave domain, powerful and compact semiconductor based sources have been developed. This motivated the development of a broad variety of different technologies including Gunn-oscillators, waveguide and quasi-optically coupled multipliers based on Schottky-diodes or varactors [1]-[4]. As thermal failure limits the maximum output power of single devices, sources with output-power levels larger than 100 mW use quasi-optically coupled distributed elements and spatial power combining to generate a single strong beam [5]. A problem of all systems based on multiplier concepts is the generation of undesired harmonics. To generate a beam consisting of a single frequency it is necessary to suppress the unwanted lower and higher harmonics. While lower harmonics can be eliminated on the detector-side using the cut-off-frequency of a rectangular waveguide in front of the mixer, higher harmonics can be eliminated by using frequency selective surfaces (FSSs). For this kind of applications, FSSs usually consist of a single or double metal screen, perforated periodically with holes and possible supported by a dielectric substrate.

In this paper, we propose the design of FSSs on thick high-resistivity silicon substrates, in order to overcome the major disadvantages of the technologies developed so far. The silicon substrate with a thickness in the 200-1000 µm mechanically supports the FSS and prevents damage as well as changes of the frequency-characteristics due to cooling or mechanical deformation of the FSS, as it often happens for free standing structures. Its mechanical stability would also allow for the application of such a device as a window material with integrated filter for vacuum shielding of cryogenic receivers/transmitters. High-resistivity silicon is one of the very few materials with extremely low dielectric loss even at higher millimeter and sub-millimeter wave frequencies. Using silicon as a substrate also enables to use highly developed and extremely reliable technologies for structuring metal on silicon, which are available from semiconductor foundries. This is the major advantage compared to other approaches [6], [7], which all require to develop a new specialized technology, resulting in very time-consuming and costly fabrication processes.

Fig. 1. Unit cell of the FSS with a rectangular aperture. The filter was designed for an incident plane wave at $\theta = 20^\circ$, $\phi = 90^\circ$, in TM-polarization.
II. DESIGN OF THE FILTER

The filter presented here is intended for transmitting the second harmonic generated by a quasi-optical multiplier array pumped at 150 GHz, and suppressing the signal at the 3rd harmonic. Therefore, to satisfy the design specs, the FSS should exhibit minimum insertion loss at 300 GHz, and present a stop-band attenuation larger than 20 dB at 450 GHz.

The structure of the filter consists of a 2 µm silicon layer, perforated periodically with rectangular slots and mechanically stabilized by an electrically thick silicon wafer, with relative dielectric permittivity $\varepsilon_r = 11.8$ (Fig. 1). The design was performed for an incidence angle of $\vartheta = 20^\circ$, in order to prevent standing waves in the quasi-optical setup.

Since the thickness of the silicon wafer is in the order of the wavelength, the structure behaves like a Fabry-Perot resonator. Therefore, in order to get maximum transmission at 300 GHz, it is necessary to align the resonance of the metal grid—depending on the slot length—and the resonance of the Fabry-Perot, which is defined by the thickness of the silicon layer. Conversely, the stop-band frequency at 450 GHz can be set by properly choosing the spacing between the slots (A and B in Fig. 1).

On the bases of these physical concepts, it is possible to select the tentative values of the geometrical dimensions of the structure. In particular, three parameters have to be set:

- the thickness $t_{Si}$ of the silicon substrate;
- the length $a$ of the rectangular slot;
- the size of the unit cell (A and B).

The thickness $t_{Si}$ of the dielectric substrate has to satisfy the Fabry-Perot resonance condition at $f = 300$ GHz:

$$t_{Si} = \frac{c}{2f\sqrt{\varepsilon_r}} \cos \left( \arcsin \left( \frac{1}{\sqrt{\varepsilon_r}} \sin \vartheta \right) \right)$$  \hspace{1cm} (1)

where $k = 1, 2, \ldots$, and $c$ is the speed of light in vacuum. For an oblique incidence angle at $\vartheta = 20^\circ$ and by choosing $k = 2$, the required thickness results $t_{Si} = 289.7 \mu m$. The design presented here is based on wafers with $t_{Si} = 302 \mu m$, because wafers with that thickness have been easily available.

Under the hypothesis $b \ll a$, the length $a$ can be determined by using the resonance condition:

$$a = \frac{\lambda}{2} = \frac{c}{2f\sqrt{\varepsilon_a}}$$  \hspace{1cm} (2)

where $\varepsilon_a$ is the effective dielectric permittivity, approximately given by $\varepsilon_a = (1 + \varepsilon_r)/2$. For a resonance at 300 GHz, equation (2) gives a slot length of $a = 197 \mu m$. Moreover, the initial value of the slot width was set to $b = 30 \mu m$.

The size $A = B$ of the square unit cell can be used to define the stop-band frequency of the filter. Due to [11], the first minimum in the transmission spectrum can occur when higher order modes can propagate. The onset of propagating higher order modes therefore coincides with the stop-band frequency of $f_{stop} = 450$ GHz. According to [12] the required size of the unit cell is given by:

$$A = B = \frac{c}{f_{stop}(\sqrt{\varepsilon_r} + \sin \vartheta \sin \varphi)}$$  \hspace{1cm} (3)

Equation 3 yields a periodicity of $A = B = 176 \mu m$ for a stopband frequency of 450 GHz. As this is smaller than the desired slot length $a$, $A = B = 176 \mu m$ is not a possible solution of the design problem. The stopband can therefore not coincide with the first minimum in the transmission spectrum of the FSS. In order to design the stopband properly the MoM-BI-RME simulation method was used to realize a minimum in the transmission spectrum at the stopband frequency. As the initial parameters could not be derived directly from equation 3, they were set to be about 25% larger than the slot size $a$ ($A = B = 250 \mu m$).

Starting from these initial parameters, the filter was optimized for minimum insertion loss at 300 GHz and stop-band attenuation at 450 GHz, by using a full-wave analysis tool based on the MoM-BI-RME method [8]. This method applies to the analysis of FSSs, consisting of single/multiple thick metal screens, perforated periodically with arbitrarily shaped apertures and possibly supported by a dielectric layer. This technique is based on the use of the Method of Moments (MoM) with entire-domain basis functions. In the case of apertures with an arbitrary shape, the basis functions are calculated numerically by using the Boundary Integral-Resonant Mode Expansion (BI-RME) method. The MoM/BI-RME method has been used for the design of FSSs operating in the microwave region [9], and in the millimeter and sub-millimeter wave range [10]. In all cases, it proved very accurate and fast (it requires few seconds for a wide-band analysis on a standard PC). Due to its rapidity, this analysis tool is particularly suited for wide-band optimization purposes.

In the optimization process based on the MoM/BI-RME method, the optimization variables were the dimensions $A$ and $B$ of the unit cell and the length $a$ of the slot, while keeping constant all other geometrical dimensions. This process permitted to obtain a filter that fulfills the design specifications. The dimensions of the optimized filter resulted: $a = 175 \mu m$, $b = 30 \mu m$, $A = B = 236 \mu m$, $t_{Si} = 302 \mu m$ and $t_m = 2 \mu m$.

III. MANUFACTURING TECHNOLOGY

The filter was machined using modern semiconductor manufacturing technologies. An aluminum layer with a thickness of $t_m = 2 \mu m$ and a titanium layer of 20 nm thickness was sputtered on the front side of the wafer and then structured using a dry etching process. Fig. 2 shows photos of the filter structure taken by an optical microscope. One can see that there is only a small rounding of the inner corners. Optical inspection of the structure showed that all the dimensions could be machined within an accuracy better than 2 µm. As we were using 100 mm wafers, there was enough space on the wafer to manufacture several 300 GHz filters with slightly varying geometric parameters and therefore slightly varying pass-band frequencies. This ensures even in the case of larger manufacturing tolerances that there will be at least one filter with the desired properties in the first run.

IV. EXPERIMENTAL RESULTS

A. Filter Characteristics

The filter spectrum was first characterized in a broad frequency range by using THz time domain (TD) spectroscopy...
and application of FFT on the time signals. The optical setup used for this investigation allowed a frequency resolution of 8 GHz and a dynamic range > 40 dB between 100 GHz and 1000 GHz. Afterwards, a CW measurement using a backward wave oscillator (BWO) was performed to characterize the filter spectrum between 290 GHz and 305 GHz. Fig. 3 shows all results of simulation and measurement. It can be seen, that there is very good agreement between both measurement results in the pass-band of the filter. The minimum insertion loss is better than 1.6 dB. Comparing the simulation and the measurement it turned out that the filters with the measured pass-band maximum at 300 GHz were those, whose resonance frequency was predicted to be 292 GHz by the simulation. The small frequency shift (about 3 %) between predicted and measured resonance frequency is very likely due to the influence of the ohmic losses on the aluminum which were not considered in the simulation. According to Fig. 3 the pass-band of the filter at 450 GHz is not situated in the first minimum of the transmission spectrum due to the comparatively large size of the unit cell. The stop-band attenuation is about 17 dB and has to be improved in order to fit the specification of an insertion loss better than 20 dB. This can be done by changing the incidence angle of the FSS as shown in the next section.

B. Fine Tuning of Stopband

After the manufacturing of the filter, the only remaining free parameter which allows to modify the filter characteristics is the incidence angle. The major advantage of this approach is the fact that the stop-band frequency can be changed by varying the incidence angle while the pass-band remains nearly unaffected. Using TD-spectroscopy we have measured the exact position of the stop-band as a function of the incidence angle. The change of the transmission in the stop-band is shown in Fig. 4 as a function of the incidence angle. A decrease of the incident angle from $\vartheta = 20^\circ$ to $14^\circ$ enhances the stop-band attenuation to more than 20 dB.

V. Results

A frequency selective surface has been applied to design a filter for harmonic suppression with a pass-band frequency at 300 GHz and a stop-band frequency at 450 GHz. The
FSS consists of an array of simple slot apertures which were realized on an aluminium layer deposited on an electrically thick silicon substrate. Initial values for the geometry of the filter structure were found and used for the optimization with the MoM/BI-RME method. Subsequently the filter was machined by modern semiconductor manufacturing technologies. Time domain spectroscopy as well as CW transmission measurement of the filter have demonstrated good agreement with simulation results. A minimum insertion loss better than 1.6 dB was achieved for the pass-band of the filter. It was found that the stop-band attenuation can be fine tuned after the manufacturing process by changing the incidence angle of the FSS. An improvement of the frequency characteristics of the FSS will be published elsewhere [13].

VI. ACKNOWLEDGEMENTS

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REFERENCES


