Micro-machined quasi-optical Elements for THz Applications

K.-F. Schuster, N. Krebs, Y. Guillaud, F. Mattiocco, M. Kornberg and A. Poglitsch

***Abstract*—We review the possibilities of micro-machined quasi-optical elements for THz radiation and report on the development of such elements at IRAM. Micro-machining of dielectrics permits us to create effective media for the THz frequency range. These media can be used to fabricate novel types of efficient quasi-optical elements. We discuss the technical challenges and compare the results of various modeling approaches with preliminary measurements.**

***Index Terms*—THz quasi-optics, Silicon micro-machining, artificial dielectrics**

I. Introduction

Micro-machining techniques and, in particular, Si micro-machining, has been recognized as an essential tool for THz technology. Most applications so far try to use micro-machining to extend existing concepts like waveguide elements and planar circuits from the millimeter into the THz range. However these techniques also allow us to create new and un-conventional quasi-optical elements. Due to its excellent properties as a low-loss dielectric, Silicon is of high interest. A key question remains the creation and modeling of artificial dielectrics. The term "artificial dielectrics" is normally used for heterogeneous dielectric material with structuresof sub-wavelength size or smaller, and for which the assumption of an effective dielectric response is a good approximation. Here we consider waves propagating nearly perpendicular to the translation-invariant direction of 1D or 2D structures. Other cases are often described as photonic band-gap materials, a class of materials which is not the subject ofthis work.

II. Silicon and possible Applications

Silicon is a unique material for THz technology for many reasons. (1) It has outstanding dielectric properties with very low loss up to 10 THz. (2) Due to its importance for semiconductor technology, it can be obtained in excellent quality. (3) There is a large variety of technologies to structure silicon and to combine it with structured metal layers or dielectric membranes, and, (4) Silicon is well suited for cryogenic applications due to its small coefficient of thermal expansion and its high thermal conductivity.

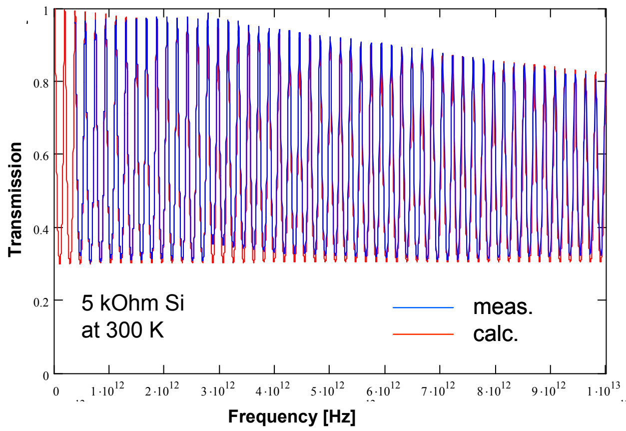

Figure 1: Transmission through a plane silicon wafer (240µm) at room temperature as measured by Fourier transform spectroscopy (FTS). The measurements can be fit up to 10 THz with good precision with a single dielectric constant and loss tangent (11.7, $\leq 7\cdot10^{-4}$).

Artificial dielectrics have a rapidly increasing impact on optical science, but also have long been used in the microwave and in the mm/submm ranges in their simplest forms like linear rectangular grooves. Silicon micro-machining has opened up the way to create artificial dielectrics in the THz range [1][2]. The relatively high dielectric constant of Si (11.7) allows tailoring of the dielectric constant of a micro-machined sample on a very broad range when using vacuum as a second medium. An example of the Si material used by us is given in Fig. 1.
The possibility to freely modulate the effective dielectric constant leads to a series of new devices in the THz range. If stacked in flat layers, high performance antireflection coatings [3][4] and dielectric filters or dichroics are possible (see Fig. 2). These devices will be well suited for cryogenic application, because layers of different dielectric constant will have the same thermal contraction and effective cooling. If the

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effective dielectric constant is modulated laterally, diffractive elements can be created like flat lenses and lens arrays.

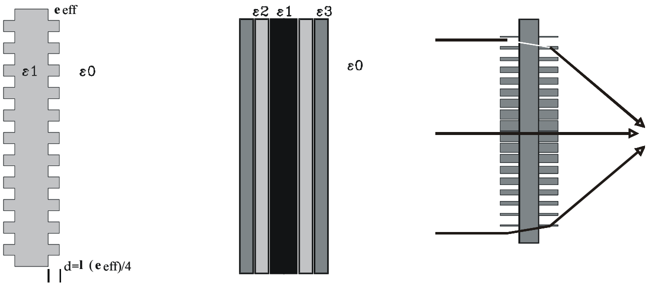

Figure 2: Planar quasi-optical elements made by micro-machining of dielectrics (matched window, dielectric filter and planar lens).

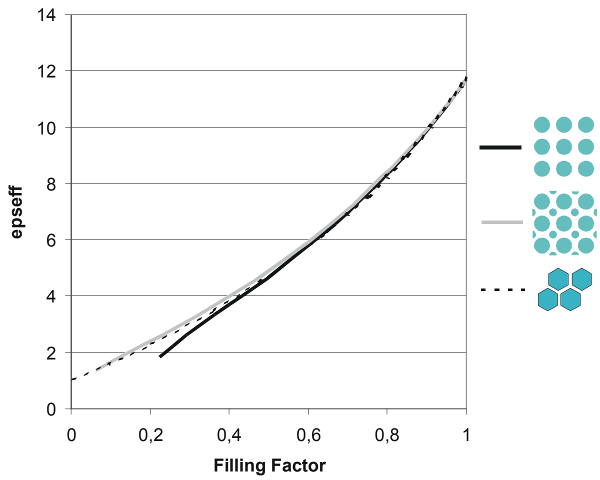

Figure 3: Low frequency effective dielectric constant versus filling factor for different isotropic patterns etched into Silicon.

III. The problem of Isotropy

While linear grooves are employed frequently for materials with relatively low dielectric constant (plastics, quartz, etc), silicon shows very strong polarization effects for such grooves. In fact the difference in ε_{eff} between co-polarized and cross-polarized waves can be as large as 200% for filling factors between 0.5 and 0.7. For most applications, this behavior is undesirable, and it is therefore of great importance to develop patterns that are polarization independent Symmetry considerations lead to the conclusion that for perpendicular incidence, only regular lattices are fulfilling these requirements, e.g. the square and the hexagonal lattice. The pattern of the individual cells can be of any shape that offers rotational symmetry of order 2 or higher (e.g. holes, polygons >4 and combinations). In optics, such materials are called uniaxial. Oblique incidence destroys the rotational symmetry of the two-dimensional patterns and will therefore generate polarization effects. As long as the incidence angles are smaller than 30 degrees, however, these effects tend to be small.

IV. Modelling

Although special cases were treated several decades ago, the general problem of modeling artificial dielectrics is a matter of current research. It is common to develop the effective refractive index n_{eff} in a power series of the structure period to wavelength ratio Λ/λ :

$$n_{eff} = n^{(0)} + n^{(2)}(\Lambda/\lambda)^2 + n^{(4)}(\Lambda/\lambda)^4 + \ldots$$

For the 0th order or low-frequency solutions linear grooves can be calculated analytically (Born & Wolf). Low-frequency solutions for more complex artificial dielectrics can be easily obtained by numerical simulations of the electrostatic case. These calculations are also useful to calculate the maximum range of effective dielectric tuning for a given pattern. In particular, hole patterns have minimum filling factors which limit the minimum achievable effective dielectric constant (see Fig. 3). Other patterns might not be used close to a zero filling factor simply because of machining tolerances and/or mechanical stability considerations.

Second-order analytical solutions exist for linear grooves and have been used to derive a practical approximation for 2nd order solutions to a square pattern [4][5]. Beyond this only numerical solutions can be found. Numerical methods include finite-element methods, conformal mapping, shoot-back methods and Fourier expansion techniques (see references in [3], [6]).

We have implemented 0th-order finite element codes for a quick check of the general behavior of different patterns and filling factors (Fig. 3). To derive higher-order solutions we have used commercial software (CST Microwave-Studio) in the time domain mode to calculate dispersion for different geometries (Fig. 4).

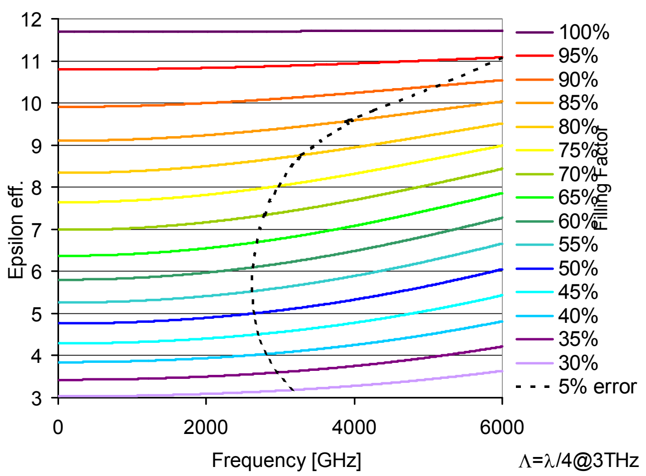

Figure 4: Effective dielectric constant of hexagonal pattern with different filling factors in Silicon as calculated with a time-domain FEM. The structure size is λ/4 at 3 THz. The area to the left of the dashed line can be approximated by the low frequency solution to within an error of less than 5%.

A question of practical importance is how large the period of any mixing pattern can be made. This will determine the machining effort required for a desired electrical behavior. In fact, two questions have to be distinguished in this respect. Firstly, one may ask how large the pattern can be made before the effective dielectric constant differs noticeably from the 0^{th}-order solution. Secondly, it is important to know at which pattern size the concept of an effective, although possibly frequency-dependent dielectric constant breaks down, because of higher-order mode propagation or diffraction effects. The answers to both questions depends on the material parameters, the detailed form of the pattern and the filling factor. Concerning the dispersion a typical result can be seen in Fig. 4 for a hexagonal pattern. For this particular case of silicon, the relative difference between the long-wavelength limit and the actual value of ε_{eff} stays below 5% for all filling factors as long as the structure period is smaller than $\lambda/4$.

The question about the validity of an effective-medium approach is more complex to answer, as several conditions have to be fulfilled independently. A necessary, but not sufficient condition, is the exclusive propagation of 0^{th}-diffraction order in the far field of the element. For perpendicular incidence it follows from the diffraction grating equation that $\Lambda/\lambda < 1/\max(n_1,n_2)$, where n_1 and n_2 are the refractive indices of the media in the front and in the back of the artificial dielectric, respectively. For silicon this condition requires $\Lambda/\lambda < 3.5$, fairly close to the requirements for relative dispersion < 5% as described above. Other conditions must be fulfilled to exclude higher-order mode propagation within the artificial dielectric, and are leading to constraints of the material index and the particular shape of the pattern [7][8].

V. First Results and Technical Challenges

As a first step in our development program, we have used 0^{th}-order calculations to design a hexagonal pattern with a filling factor 0.35. This corresponds to an effective low-frequency dielectric constant of 3.42, the geometrical mean of Si and vacuum/air and as required for matching between these medias. The distance of two cells was 51µm (See Fig. 5). The hexagonal pattern offers the advantage of being mechanically very rigid and well suited for low filling factors.

A Si-wafer of 240µm thickness was etched from both sides with the designed pattern to a nominal depth of 22µm and the transmission was measured at room temperature in an intermediate waist of the optics of a commercial FTS spectrometer (see Fig. 6). The result shows a matching very close to 2 THz with a matched bandwidth of greater than 30% for transmission above 90%. The measurements can be described well with a simple transmission line model up to 2 THz. Above this frequency, the model fails due to diffraction and excitation of higher-order modes.

New ways of measuring planar devices are under development at IRAM. These include setups with mm-wave network analyzers and resonant cavity measurements which will give complete amplitude and phase information as well as antenna range measurements to characterize polarization-dependent off-axis scattering.

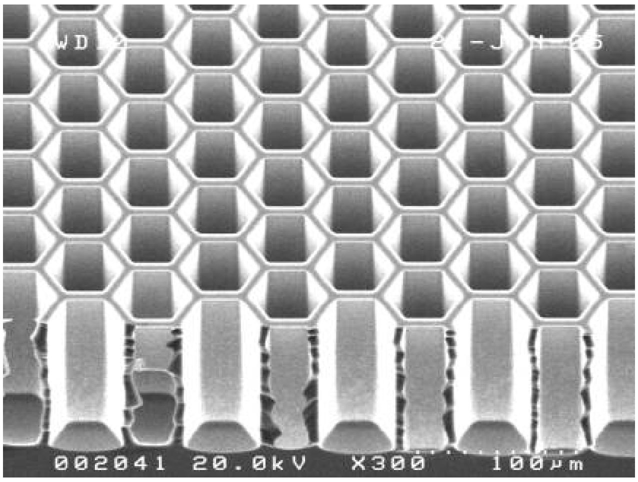

Figure 5: Micrograph of a hexagonal pattern as machined with deep Silicon etching and an effective dielectric constant close to 3.42, as required to match air and silicon.

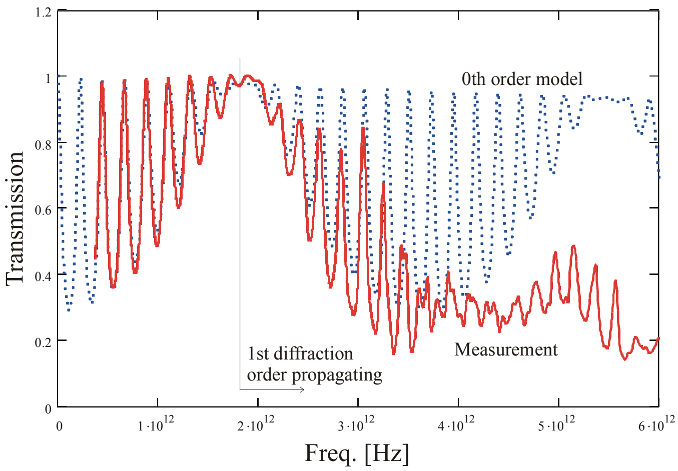

Figure 6: Transmission of a silicon wafer at room temperature with micro-machined matching layer for 2 THz (FTS measurement). Above 2 THz, the simple transmission line model using the 0^{th}-order solution breaks down.

Future technical challenges include improving the control of etch depth as well as aspect ratio dependent etching effects (ARDE). Further on, it will be necessary to study etch-induced surface damage or pollution and its consequences for the THz properties of the samples.

Future modeling must include finite angles of incidence and propagation of higher-order modes.

VI. Conclusion

Silicon micro machining allows tailoring of artificial dielectrics for the THz range with a widely adjustable dielectric constant. First simple examples of polarization independent quasi-optical elements have been successfully designed and fabricated. Next steps will include improved modeling and the design of planar diffractive elements.

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