Planar silicon metamaterial lenses with integrated anti-reflection coatings for frequencies around 150 GHz

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For quasi-optical elements in the millimeter and sub-millimeter range, silicon is an interesting material. Its high refractive index facilitates the production of compact and lightweight elements. Moreover, its thermal conductivity allows better thermalization at cryogenic temperatures, and the loss tangent of bulk high-resistivity silicon (tan δ < 10-4) is without competition.

Silicon is however very difficult to machine, and the high refractive index necessitates the use of anti-reflection coatings. Micromachined anti-reflection coatings have been developed for planar substrates but become increasingly more difficult for curved surfaces of e.g. lenses.

In this work, we follow a different approach. We use the fact that it is possible to modulate the refractive index of a material by inserting sub-wavelength voids and changing the fill factor of the voids. This way, a silicon metamaterial with a dielectric constant between 3.3 and 11.7 can be generated [1].

From (visible) optics it is well known that a curved surface, such as a lens, can be mimicked by a planar element that has the appropriate refractive index gradient. Thus, we designed a planar silicon element, with an expected focal length of 180 mm. The lens has a diameter of 50 mm, and the effective dielectric constant varies continuously from 11.2 in the center to 3.3 at the edges of the lens, by the means of an hexagonal array of holes with a period of 104 µm and a hole size varying from 13.4 µm in the center to 81 µm at the edges. The total thickness of the lens is 1 mm, which is about an order of magnitude thinner than an equivalent (curved) polyethylene lens with a similar focal length.

The element was fabricated out of four 250 µm thick, high-resistivity silicon wafers that were micromachined using a Bosch process in an inductively coupled plasma etcher. The wafers were aligned using dowell pins, and pressed together in a dedicated holder. The same process was used to fabricate two anti-reflection coating layers, using 250 µm wafers with an adapted dielectric constant profile, such that the dielectric constant is given by $\varepsilon AR(x) = \sqrt{\varepsilon lens(x)}$. The thickness of the AR coating is chosen such that the averaged reflection over the surface of the lens is minimized, since the optimal quarter-wave adaptation is impossible using a planar design with varying dielectric constant. The modular design of our devices easily allows for more intricate AR coatings consisting of multiple layers of varying thickness and dielectric constant.

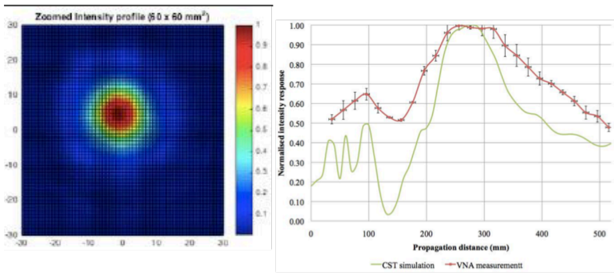

Fig. 1. (left) Measured beam profile of a microwave feed horn imaged by the silicon metamaterial lens. (right) On-axis intensity as a function of distance, measured (red) and as simulated with CST (green). Both measurements and simulations are made at a frrequency of 150 GHz.

The fabricated lens was subsequently characterized in an antenna range. We find that the imaging properties of the lens are excellent, but that the effective focal length is approximately 30% smaller than designed. The measured value is confirmed by CST simulations of the structure (see Fig. 1). This difference is attributed to the fact that the lens is of comparable thickness to the wavelength, privileging near-field effects, and rendering ray-optical approaches such as used for the design insufficient. Simple transmission measurements indicate the effectiveness of the AR coating.

The presented technology offers great perspective in terms of compact, planar, low-loss optics. Moreover, the technology can be easily integrated with silicon detector wafers, and future developments that involve more elaborate anti-reflection coatings, integrated filtering, or microlens arrays, are just part of the possibilities.

We will discuss further optimization of this technology towards actual optical elements for radio-astronomy applications, as well as the current limitations of the used technology.

REFERENCES

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