Strongly confined metamaterial-mediated terahertz surface waves on silicon

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Abstract

We present experimental and numerical investigations on the excitation and optimization of strongly confined metamaterial-mediated terahertz surface waves on silicon substrates. It is shown that the spatial confinement of terahertz surface waves can be strongly enhanced by a single mediating metamaterial layer located between silicon and air. The design of the metamaterial layer is based on an array of split-ring resonators. The propagation length of the confined surface waves was several millimeters with a free space wavelength of one millimeter. An experimental measurement of the terahertz transmission spectrum showed excellent agreement with the numerical calculations and evidenced the excitation of surface waves.

1. Introduction

Metamaterials are artificial materials with unique electric and magnetic properties. The response of a metamaterial to an external electromagnetic field is determined by the microscopic structure of small constituent unit cells rather then by the chemical composition of the medium. If the size of the unit cell is well below the operating wavelength, the electromagnetic response can be described by effective material parameters. The material parameters can reach values which may not be available in conventional materials. It has been shown that, under special conditions, thin metallic metamaterial films support surface waves which behave much like surface plasmon polaritons (SPPs) on metal-dielectric interfaces [1, 2]. Due to the high conductivity of most metals at terahertz (THz) frequencies, SPPs are only weakly bound on flat metal surfaces. But especially in the terahertz regime, confined surface waves have gained growing attention in the last decade because of the manifold possibilities of enhancing the interaction with matter opens new routes for sensing applications. In particular, metamaterials offer a great possibility to increase the confinement of surface waves at will by tuning the effective material parameters.

2. Design, fabrication and experimental results

We demonstrate a metamaterial-based design that significantly enhances the confinement of surface waves at the interface between silicon and air. The metamaterial consists of a single layer of split-ring resonators (SRRs) which exhibit a magnetic resonance at 0.3 THz. The unit cell size of the structure is $a = 50\,\mu\text{m}$, which corresponds to $\lambda/6$ of a propagating wave in silicon at a frequency of 0.3 THz. This subwavelength unit cell size legitimates the description by effective medium theory.

Fig. 1 shows the calculated dispersion relation of the surface waves together with the light lines of air and silicon. At frequencies higher than 0.24 THz, the waves are bound to the surface with wave vectors

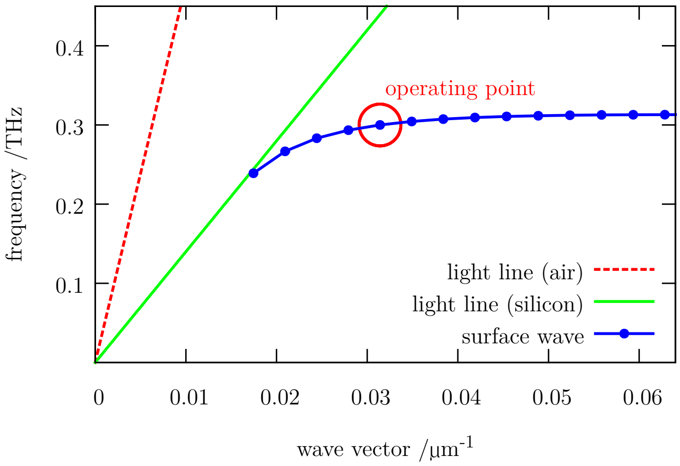

Fig. 1: Dispersion relation of the surface wave: The branch of the bound surface wave is located "right" to the light lines in air and silicon.

larger than the wave vector of freely propagating waves in both air ($n \approx 1$) and silicon ($n \approx 3.4$). In order to obtain confined surface waves, the effective refractive index at the surface must be larger than the refractive index of silicon. At an operating frequency of 0.3 THz, the effective refractive index of the metamaterial-mediated surface was $n_{eff} \approx 4.2$. Note that, in contrast to conventional surface waves e. g. on metal sheets, the magnetic field is normal to the surface.

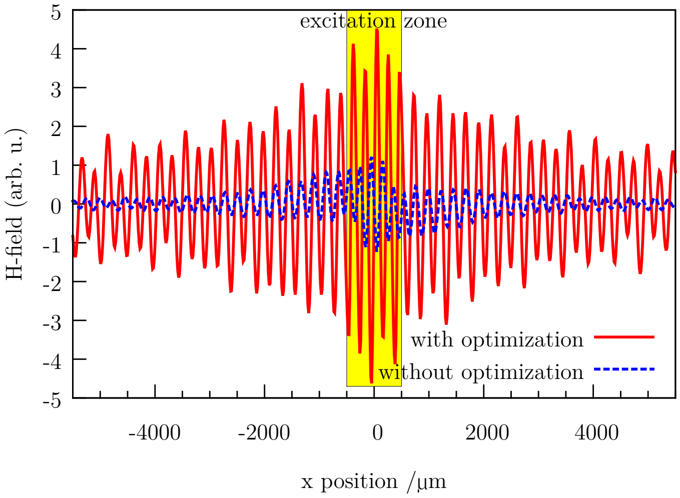

Fig. 2: Magnetic field H in dependence on the position x. Impedance matching optimization between the excitation and propagation zones significantly improves the coupling efficiency.

For the excitation of surface waves, we added an artificial grating as an excitation zone to the metamaterial structure by leaving out every fourth row of SRRs [3]. The length of the excitation zone was 1 mm while the propagation zone of the surface waves was larger than 5 mm. The grating had a spatial period $a = 200\,\mu\mathrm{m}$ which corresponds to a reciprocal grating vector $k_{sw} = 2\pi/(4a)$. Under this condition, the grating allows the coupling of THz waves with a wavelength of $\lambda = 200\,\mu\mathrm{m}$ to confined surface waves at the interface. Excitation of the surface waves occurs due to magnetic field coupling between the incident THz radiation and the magnetic resonance of the SRRs. We optimized the individual resonance frequencies of the SRRs in the excitation and propagation zone to obtain matching of the effective

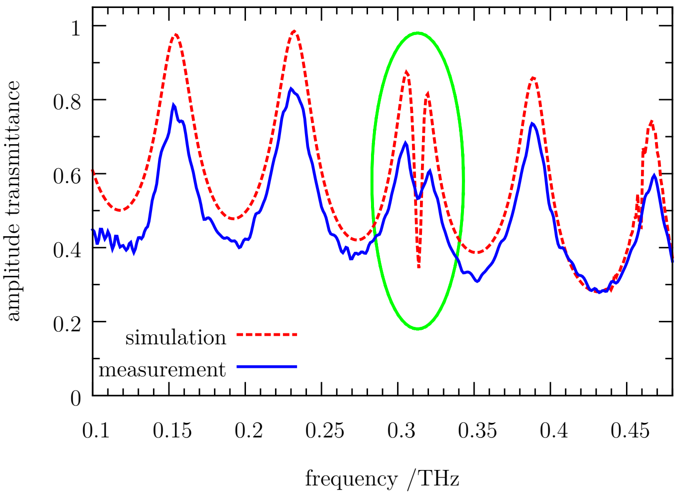

Fig. 3: Comparison between the calculated and measured terahertz transmission spectrum: The excitation of the surface waves causes a narrow transmittance minimum at 0.32 THz.

impedances of both zones. For the optimal parameter set we achieved a coupling efficiency of up to 75% at 0.3 THz. Fig. 2 shows the calculated magnetic field H in dependence on the position x in the propagation direction of the surface waves with and without optimization of the grating and propagating zones. The excitation zone is located between $x = -500 \ldots + 500\,\mu\text{m}$. The surface waves propagate over a length of the order of several millimeters. As can be seen, impedance matching significantly improves the coupling efficiency. To compare our simulation data with experimental results we measured the transmission spectrum of the fabricated metamaterial structure on silicon by THz time-domain spectroscopy. Fig. 3 shows the amplitude transmission of an incident TE-polarized THz beam (electric field parallel to the grating lines). We observed a narrow-band transmission minimum at 0.32 THz which indicates the excitation of metamaterial-mediated surface waves at the silicon-air interface. The frequency of the experimentally observed transmission minimum is in excellent agreement with the results obtained from full wave simulations.

3. Conclusion

In conclusion, we have presented experimental and numerical results on strongly localized metamaterial-mediated terahertz surface waves on silicon substrates. We demonstrated the excitation by using a grating coupler with a coupling efficiency up to 75% and the optimized propagation of surface waves with a propagation length of several millimetres corresponding to a free space wavelength of one millimeter. The potential of our metamaterial design to confine THz waves to a stable, solid substrate may lead to new designs of integrated terahertz systems and promises applications in sensing and waveguiding.

References

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