An oscillator-based sensor using a capacitive metal mesh for sensitive detection of dielectric materials in the terahertz region

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Abstract: An oscillator-based sensor is proposed that uses a surface-wave resonance effect that happens in a capacitive metal mesh to detect dielectric materials sensitively in the terahertz region. Experiments performed at frequencies around 0.1 THz show that the oscillator-based sensor has a high sensitivity of 2.6 GHz/RIU (refractive index unit) and can identify a small difference of 3.8×10^{-4} in the refractive index of a dielectric material.

Keywords: metal mesh, surface wave, sensor, terahertz wave

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Resonance effects of surface waves (SWs) induced in inductive mesh structures involving a metal film perforated with subwavelength hole arrays have attracted much attention in the terahertz (THz) region [1]. The SW resonance causes an anomalously high peak transmission in inductive metal meshes at specific frequencies [2]. These resonant frequencies are extremely sensitive to any dielectric medium surrounding the inductive mesh and thus are changed considerably by putting a small amount of dielectric material on the mesh surfaces [3]. Inductive meshes with these unique features have been used as highly sensitive sensors [4] and to control transmission [5]. To date, most investigations of these SW resonance effects have been for inductive mesh structures. However, although the SW resonance happens also on capacitive metal meshes (see Fig. 1), there have been only a few such experimental reports [6, 7]. In this letter, we propose an oscillator-based sensor (OBS) with a capacitive metal mesh as a novel means of detecting dielectric materials sensitively in the THz region.

2 Capacitive metal mesh

Fig. 1 shows (a) inductive and (b) capacitive metal meshes with grating period g and gap $2a$ on a dielectric substrate. The resonant frequency of SWs on the meshes is determined mainly by the period g and the effective refractive index n of the dielectric materials adjacent to the mesh surfaces [8]. For normal THz-wave incidence, the lowest resonant frequency f_0 is given by $f_0 = c/ng$, where c is the speed of light. This equation indicates that f_0 depends strongly on n . As a result, the transmission properties of the mesh also change considerably.

As shown in Fig. 1, a capacitive mesh has a structure that is complementary to that of an inductive mesh, and thus the SW resonance in the former causes not

Fig. 1. (a) Inductive and (b) capacitive metal meshes on dielectric substrates. The mesh parameters g and $2a$ are the grating period and the gap between neighboring square patterns, respectively.

extraordinary transmission but extraordinary reflection [9]. This reflection property of a capacitive mesh is suitable for an OBS in which a capacitive mesh is used as one of the reflectors in the oscillator and as a sensor of dielectric materials on its surface.

3 Experimental setups

Fig. 2 shows the experimental configuration of the OBS used to demonstrate its effectiveness at THz frequencies around 0.1 THz (100 GHz). It consists of a standard *W*-band rectangular waveguide with a Gunn diode, a horn coupler, and a capacitive metal mesh. The Gunn diode used can oscillate in the fundamental mode at frequencies of 80–100 GHz. The horn coupler has a rectangular aperture of 18.7 mm × 24.6 mm and a length of 49.2 mm. The capacitive mesh was designed to resonate at 95 GHz using the ANSYS HFSS electromagnetic-field simulator. It was then fabricated using aluminum evaporation and photolithography on a quartz substrate with dimensions of 30 mm × 40 mm × 0.31 mm. The fabricated mesh has the parameters of $g = 2$ mm and $2a = 0.8$ mm. The transmission property of the mesh was measured by the free-space method [10] with a vector network analyzer (VNA; N5442A, N5256AX10, Keysight Tech.) in the *W*-band (75–110 GHz). The measured results showed that the mesh had power reflection coefficients higher than 0.9 at frequencies of 89–98.8 GHz. The maximum reflectance was 0.96 at 96.3 GHz. Refractive indices of dielectric sample plates described later were also measured by using the free space method in the VNA. The uncertainty of the measured refractive indices was ± 0.01 .

Fig. 2. Experimental setup. D.C. stands for directional coupler.

In Fig. 2, the mesh and a dielectric sample plate were set on precision mirror mounts on linear translation stages with micrometer heads. The linear stage travel is 10 mm and the accuracy of positioning is ± 5 μ m. Firstly, the mesh is placed in front of the horn coupler and the angle of the mesh is adjusted to be the maximum in the output power of the oscillator. A dielectric sample plate then is set and its angle is carefully adjusted to be parallel to the mesh surface so that the sample can make contact with the mesh surface without a notable gap at the distance $L = 0$.

As seen from Fig. 2, the capacitive mesh and the Gunn diode form a resonator in the OBS. The oscillation frequency is thus changed by adjusting the distance L_0 between the mesh and the horn coupler. The oscillation frequency f_{osc} and the output power P_{out} were measured for various dielectric samples by using a power meter with a power sensor (HP437B, W8486A, Hewlett Packard) and a spectrum analyzer (HP8563E, Hewlett Packard) connected to a mixer (11970W, Keysight Tech.) and a 20-dB directional coupler. In the experiments, we measured mainly

variations in f_{osc} for dielectric samples with different refractive indices to demonstrate the high sensitivity of the OBS as the first step of the investigation.

4 Results and discussion

Fig. 3 shows (a) the measured oscillation frequency f_{osc} in the OBS without a dielectric sample as a function of distance L_0 , and (b) the output power P_{out} as a function of f_{osc} . As seen from Fig. 3, the range of oscillation frequency is 95.7–97.8 GHz and the maximum output power is 42.7 mW at 96.6 GHz. From the ratio of f_{osc} to L_0 shown in Fig. 3(a), the free spectral range (FSR) in the OBS was estimated to be 2 GHz at 97 GHz. This FSR limits the maximum refractive index of a dielectric sample measured by the OBS because f_{osc} changes continuously only in the FSR without longitudinal mode hopping.

Fig. 3. (a) Measured oscillation frequency f_{osc} in the Gunn-diode oscillator as a function of distance L_0 between the mesh and the horn coupler. (b) Output power P_{out} as a function of oscillation frequency.

Fig. 4(a) shows the measured variations in f_{osc} of the OBS for two quartz samples as a function of the spacing L between the mesh and the sample. QP95 and QP160 are quartz plates with the same dimensions of 30 mm × 40 mm but different thicknesses of 0.095 mm and 0.16 mm, respectively. The refractive indices of the quartz plates including the quartz substrate of the mesh were the same, namely 1.95, which were measured using the VNA. In the experiment, f_{osc} was set to be 97 GHz at $L = 1$ mm by adjusting L_0 prior to the measurements. Fig. 4(b) shows the variations in the reflection phase at the mesh measured using the VNA for the same experimental configuration of the mesh and quartz samples at 97 GHz. The reflection phases indicated in Fig. 4(b) are phase shifts from the phases measured at $L = 1$ mm.

In Fig. 4(a), when L decreases from 1.5 mm to zero, f_{osc} is almost constant until $L \approx 0.4$ mm and then falls off abruptly and almost exponentially with L , finally reaching 96.77 GHz for QP95 and 96.6 GHz for QP160 at $L = 0$. Comparing the results in Fig. 4(a) and (b) indicates that the variations in f_{osc} are caused mainly by the variations in the reflection phase at the mesh. Furthermore, the exponential variations of the reflection phase in Fig. 4(b) clearly show that those variations

arise from the SW resonance effect that happens at the mesh. As described in [11], SWs on the mesh are evanescent waves and their decay length z_0 is given by $z_0 = (\lambda/2\pi)/\sqrt{(\lambda/g)^2 - 1}$, where λ is the wavelength of the wave incident on the mesh. Using this equation, the value of z_0 for SWs in the capacitive mesh at 97 GHz is estimated to be 0.42 mm, which is consistent with the measurements.

In the experiments, the output power P_{out} in the OBS also decreased from about 42 mW at $L = 1$ mm to 39.2 mW for QP95 and 32.2 mW for QP160 at $L = 0$. This reduction in P_{out} was due to two factors, one being the reduction of the reflection coefficients of the mesh due to the SW resonance effect and the other being the dielectric loss of the samples. These two factors could be distinguished by measuring the power transmitted through the sample by the OBS; this remains as future work.

Fig. 4. Measured variations in (a) oscillation frequency in the oscillator-based sensor (OBS) and (b) reflection phase at the capacitive mesh as a function of the spacing L between the mesh and the quartz-plate samples QP95 and QP160. The phase changes were measured using the free-space method with a vector network analyzer (VNA) at a frequency of 97 GHz.

Fig. 5 shows the measured frequency shifts of f_{osc} from 97 GHz in the OBS for the following dielectric samples at $L = 0$: plates of polytetrafluoroethylene (PTFE), polyethylene (PE), polymethyl methacrylate (PMMA), and polyvinyl chloride (PVC). The thicknesses of the four sample plates were $1 \text{ mm} \pm 25 \mu\text{m}$, which were chosen to be greater than $z_0 = 0.42 \text{ mm}$. The surface flatness of the samples were smaller than $5 \mu\text{m}$. The refractive indices of PTFE, PE, PMMA, and PVC were 1.43, 1.53, 1.62, and 1.65, respectively, which were also measured using the VNA.

As seen from Fig. 5, f_{osc} decreases monotonically with refractive index because of the SW resonance effect. The difference of 0.03 between the refractive indices of PMMA and PVC changed f_{osc} by 80 MHz, thus the OBS sensitivity is around 2.6 GHz/RIU (refractive index unit) at a refractive index of 1.62. The oscillation frequency f_{osc} in the OBS fluctuated within 1 MHz in the time period of the measurements because of small temperature changes and mechanical vibrations. As a result, it is seen that the OBS can distinguish a small difference of 3.8×10^{-4} in refractive index, which is only 0.023% for a refractive index of 1.62. Because the

oscillation frequency bandwidth at full width at half maximum in the OBS itself is less than 40 kHz at the center frequency of 97 GHz, the detectable difference in refractive index could be reduced to 1.5×10^{-5} by applying thermal stabilization and vibration isolation to the OBS.

Fig. 5. Measured oscillation spectra in the OBS for dielectric samples of PTFE, PE, PMMA, and PVC at $L = 0$. The abscissa is the frequency shift from 97 GHz, which is the oscillation frequency in the OBS without the samples.

5 Conclusion

An OBS that uses the SW resonance effect on a capacitive metal mesh was proposed as a highly sensitive sensor for detecting dielectric materials in the THz region. Experiments performed at frequencies around 0.1 THz showed that the OBS has a high sensitivity of 2.6 GHz/RIU and can distinguish dielectric materials that differ by only 3.8×10^{-4} in refractive index. These results indicate that an OBS is a potential means of detecting dielectric materials including liquid in the THz region.