Terahertz Metamaterials Application in Sensing Bacteria and Fungi

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***Abstract*—We fabricated THz metamaterial sensors for sensitive, on-site detection of microorganisms such as fungi and bacteria. Strong field localization and enhancement in a gap area enables us to detect the microorganisms with high sensitivity, in aqueous and ambient conditions. The resonant frequency shift is investigated as a function of the dielectric constant and shape of the microorganisms. To optimize microbial sensors, the sensitivity has been studied with respect to substrate dielectric constant and geometrical parameters of the gap structures.**

I. INTRODUCTION

Detections of biological substances such as fungi, bacteria, and virus have been of particular interests in the terahertz (THz) frequency range for the purpose of food and security inspection. There has been hardly any progress since they are mostly transparent against THz waves. On the other hand, metamaterials have been studied extensively to develop useful biosensors. In particular, THz metamaterials have micro-gap structures that are compatible with the sizes of the microorganisms. Here we demonstrate that metamaterials operating in the THz frequency range shows promising potential for use in fabricating the highly sensitive and selective microbial sensors that are capable of high-speed on-site detection of microorganisms in both ambient and aqueous environments [1].

II. RESULTS

We fabricated THz metamaterials such as split-ring resonators (Fig. 1a) and slot antenna arrays by using a photolithography technique. A clear shift in the resonant frequency is observed following the deposition of microorganisms, which arises due to the change in the effective dielectric constant in a gap area of the metamaterials structures. Strong field localization and enhancement in the gap area enables us to detect the microorganisms with high sensitivity. We were able to detect extremely small amounts of fungi and bacteria, in other words, even in the case when the average number in the gap area was less than unity.

In particular, the resonant frequency shift is higher for the microorganisms with larger dielectric constants. As shown in Fig. 1b, we found that yeast cells are more sensitive than the penicillium in terms of the frequency shift, which was successfully interpreted by the dielectric constant measurements of the individual fungi. In addition, as shown in Fig. 1c, our THz metamaterials sensors can be applied in aqueous conditions as easily as in ambient conditions. This is because the THz metamaterial is extremely sensitive to the substances located near the surface, allowing us to use a thin water layer without suffering from the poor transmission in conventional THz spectroscopies. THz metamaterial sensing is a universal method because it is based on the dielectric sensing, while a selective detection is also possible by functionalizing the substrates with antibodies specific to the target substances (Fig. 1c).

To design optimized microbial sensor, the sensitivity of THz metamaterials has been studied as a function of the substrate dielectric constant, gap size and the metal film thickness [2]. In particular, sensors fabricated on a substrate with relatively low permittivity demonstrate higher sensitivity (Fig. 1d). The frequency shift decreases with increasing gap width for a fixed coverage of yeast, showing a field enhancement effect. Furthermore, the vertical range of the effective sensing volume has been studied by varying the thickness of the yeast film.

Our experimental findings are in a good agreement with the results of finite-difference time-domain (FDTD) simulations. We revealed that the shape of the individual microbes also influences the sensitivity, which is confirmed experimentally by using microbeads with various shapes. Our work shows promising potential for use in the fabrication of highly sensitive microbial detectors that are capable of high-speed on-site detection of hazardous microorganisms in various environments.

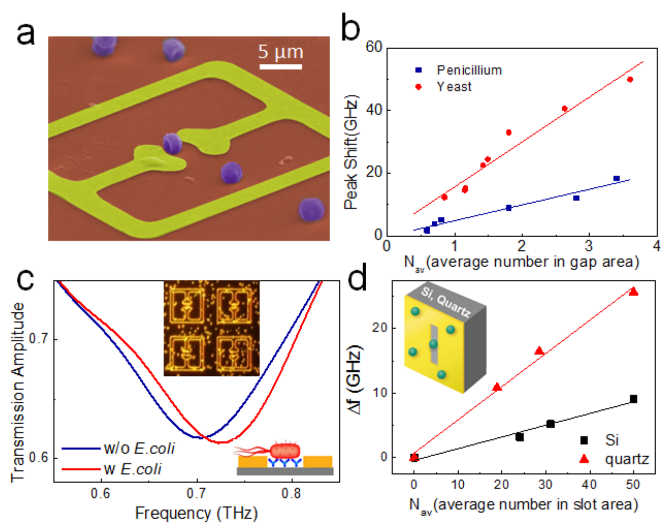

Fig. 1. (a) SEM image of metamaterials coated by penicillia. (b) A plot of resonant frequency shifts as a function of N_{av}, for depositions of penicillia (blue boxes) and yeasts (red circles). Solid lines are linear fits to the data. (c) THz transmission before (blue line) and after (red line) the deposition of E. coli. on the functionalized metamaterials in aqueous environments. (Inset) A corresponding dark-field microscopic image obtained after the deposition of E. coli. (d) Resonant frequency shift of THz slot antenna as a function of yeast number in the slot area, for both Si and quartz substrates.

REFERENCES

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