Designing Bull's eye structures for non-destructive inspection using GHz waves and carbon nanotube film

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1. Introduction

Corrosion of metals in concrete due to aging is an important problem in reinforced concrete buildings. Recently, we have developed a method to measure metal corrosion inside concrete using GHz wave [1]. We have also demonstrated that our carbon nanotube (CNT) sensor can detect GHz waves, enabling its applications in non-destructive inspection [2]. This sensor detects electromagnetic wave using the electromotive force generated by the thermal gradient between the wave-irradiated area and the rest of the region, and thus the detection efficiency depends on the beam size. However, it is difficult to reduce the beam size of GHz waves, which have a wavelength of around 10 cm. This is because the beam size is limited to the wavelength due to the diffraction limit. Therefore, generating a significant thermal gradient with GHz waves is challenging. Here we use the Bull's eye (BE) structure including one aperture with a bowtie shape, where the shorter gap width is 0.6 mm, to achieve GHz wave confinement beyond the diffraction limit.

2. Experiment

Figure 1a shows the designed BE structure modeled by a perfect electric conductor in air. A linearly polarized plane wave along the y-axis is used as an incident wave. The energy density of the electromagnetic fields was calculated at plane 200 μm below the aperture using electromagnetic simulation based on the finite-difference time-domain (FDTD) method. We defined the energy density enhancement as the ratio of the energy density with the structure to that without the structure.

3. Results and Discussions

As shown in Fig. 1b, the BE structure exhibits resonance at around 14.16 GHz, where the energy density enhancements exceeding 1600 are achieved. Figure 1c shows the line profile of the energy density enhancements along the shorter gap at the resonant frequency (14.16 GHz). Despite the incident GHz wave with a wavelength of about 2.1 cm, the waves with strong energy density enhancement were confined within a gap of 0.6 mm. This result can be considered as sufficient energy concentration because the length of the CNT sensor is more than 10 times larger than the gap width.

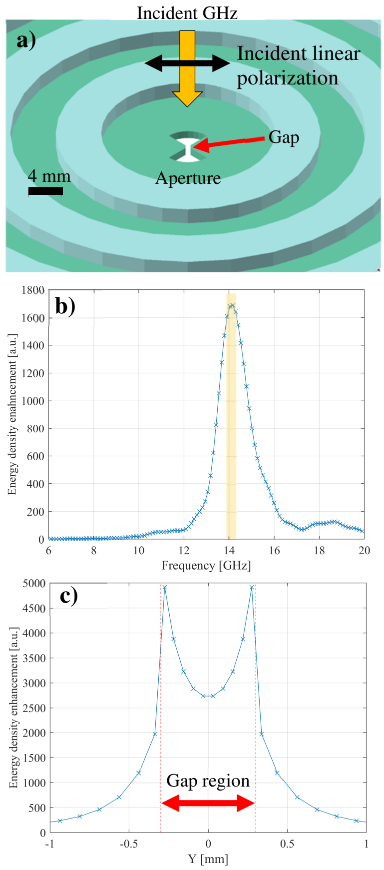

Figure 1. (a) Designed BE structure. (b) The energy density enhancement spectrum of BE at point 200 μm below the center of the aperture. (c) Line profile of the energy density enhancement of BE at 200 μm below of the aperture.

4. Conclusion

We have demonstrated through electromagnetic field calculations that focusing GHz waves beyond the diffraction limit is possible using a BE structure with a tiny aperture gap. Combining this BE structure with a CNT sensor could potentially improve the response voltage of the sensor from the conventional few μV range to several mV. This enhancement enables wireless non-destructive inspection through the antenna using a simple microcontroller with Wi-Fi functionality and an amplifier circuit.

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6. References

[1] H. Okawa, T. Oohashi, T. Tanabe, I. Sato, and Y. Kawano, the 2023 Autumn Meeting of the Japan Inst. Metals (2023).
[2] K. Li, Y. Kinoshita, D. Shikichi, M. Kubota, N. Takahashi, Q. Zhang, R. Koshimizu, R. Tadenuma, M. Yamamoto, L. Takai, Z. Zhou, I. Sato, and Y. Kawano, Adv. Optical Mater. 2302847 (2023).