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Guided tapered slot antenna for near field millimeter-wave imaging

#Shoji Mochizuki[1], Souichi Oka[1], Naoki Matsumiya[1],
Hiroyoshi Togo[2] and Naoya Kukutsu[2]
[1] Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation
1-7-1 Hanabatake, Tsukuba, Ibaraki, 305-0805 Japan, mochizuki.shoji@lab.ntt.co.jp
[2] Microsystem Integration Laboratories, Nippon Telegraph and Telephone Corporation
3-1 Wakamiya, Morinosato, Atsugi, Kanagawa, 243-0198 Japan

1. Introduction

The deterioration of concrete structures built long years ago has been a serious social problem. One of the assessment indexes for the durability of the concrete structures is surface crack, which allows water to easily penetrate into concrete and rust reinforcing bars. An acceptable width of the crack, which differs by country, is usually 0.3 mm in dry air and less than 0.2 mm in humid air. Although visual inspection is the most widely used method for non-destructive testing, it cannot be used to cracks covered e.g., by wallpaper, tile, paint, and repair material. Using a near-field millimeter-wave, NF MMW, imaging technique we proposed [1] provides the location of the invisible cracks by seeing through covering material. However, it is too blurry to recognize cracks with a width of under 0.2 mm wide because of superposition between surface scattering from the crack and volume scattering from aggregates in the concrete. An NF MMW imaging with image reconstruction techniques such as a holographic technique [2] can focus on surface cracks away from 0.1-mm deeper aggregates, that is, increase crack signal and decrease the other ones. To use this technique, a 77-GHz-band monostatic-radar module with a constant-width antipodal tapered slot antenna (TSA) and in-phase and quadrature detection has been developed and achieved good phase sensitivity corresponding to a resolution of 0.01 mm in concrete [3]. However, a TSA designed based on far-field calculation illuminates a wide area in the near-field region of around a wavelength. It is not suitable for imaging a narrow crack with a small signal which is almost the same variation level as that of the other signal, that is noise, scattered from aggregates in the concrete. We propose a guided TSA locally illuminating to the near-field region to improve crack signal to noise ratio of the received signal.

2. Near-field imaging for invisible surface crack detection

The near-field imaging system we designed for crack detection of a concrete surface is shown in Figure 1. The system consists of a monitor, a battery, and a sensor which contains linearly arrayed radio-frequency (LARF) modules operating in the 76-77 GHz band, an RF switch and a baseband circuits, a rotary encoder, and central processing unit. The LARF modules, each of which has a transmitter, a receiver and the TSA [3], are placed less than a few wavelengths away from the surface. While received signals from concrete surface and non-metal substance covering the concrete surface are almost constant by moving the sensor along a covered concrete surface, the variation of received signals is observed near the surface crack and a downward peak is observed at the crack. Therefore, the crack image can be shown in the two-dimensional MMW image.

3. Antenna design for near-field imaging and simulation result

In practical use, the target distance between antenna and crack is around 5 mm (about 1.3 wavelength) that is about 1-mm thick body of the sensor, and about 2-mm gap between the sensor body and the covering material with about 2-mm thickness. An open-ended waveguide (OEWG) with a small aperture and low gain can be used as an antenna for NF MMW imaging. However, its NF decreases too rapidly in the distance to use as an antenna of NF imaging while seeing through covering materials over a wavelength distance. On the other hand, the TSA we designed previously for the LARF modules with high gain, low loss and small aperture has higher penetration depth than OEWG. Many clutter signals from aggregates in the concrete as well as the crack signal are received because of its wide illumination to the near field. Local illumination and high penetration depth are required for the antenna of the NF imaging to be able to allow the user to visualize surface cracks under covering material. Although a mirror or a dielectric lens with a large aperture can be used to focus a beam in the case of the far-field MMW imaging such as navigation and security application [4,5], it is too large to be acceptable for NF imaging. In particular, the pitch of the LARF modules for crack detection should be around less than 5 mm in the Z-axis because it is found experimentally that the visibility of the crack in the MMW image is significantly worse due to the lack of the crack connectivity in the Z-axis.

To localize the illumination to the NF and high penetration depth with a small aperture, we designed a guided TSA (GTSA) for NF imaging as shown in Figure 2. The metal guide surrounding the TSA [3] with a gap of 1 mm in the X-axis and 1.58 mm in the Z-axis encloses electromagnetic field in the cavity and propagates it to aperture with 3.25- and 4.2- mm of the height (H) and the width (D), respectively. The GTSA is fed by a microstrip line, MSL, and the wave on the MSL is transformed to a slot-mode by a balun in the mode transition region. There are three waves in the slot-mode propagation region, i.e., one is in the TSA, the others are in the gap between the TSA and the guide. All of their waves are superposed in the region in front of the TSA in the guide. The region works as a function of the phase matching, which is 2 mm long, and the wave then radiates in the forward direction locally and effectively.

To design the GTSA for NF imaging and optimize the parameters that is S, L, and H of it in Figure 2, numerical simulations were carried out and the results of the NFs were compared with those of the TSA. The 2-dimensional distributions of calculated intensity of Ex-field near the TSA and GTSA in the XY- and XZ-planes is shown in Figure 3. The colormap is plotted in logarithmic scale, and each value is normalized to a peak one in its plane. The TSA illuminates a wide area because the wave seeping out to the free space with traveling on the TSA. On the other hand, the GTSA illuminates a local area by the guide enclosing and propagating the wave on the TSA. The comparisons in calculated intensity of Ex-field between the TSA and the GTSA along the X- and Y-axes are plotted in Figure 4, respectively. The 3-dB beamwidth of the GTSA is 4 mm while that of the TSA is 8 mm. The intensity of Ex-field of the GTSA at a distance of 5-mm is 4.9 dB higher than that of the TSA. It is found that the GTSA provides local illumination and good penetration of substance covering concrete structures.

4. Conclusions

To improve the crack signal to noise ratio of the received signal in LARF modules of the NF MMW imaging system for detecting the invisible surface crack with a width of less than 0.2 mm of concrete structures, a guided TSA with localized illumination, which reduces receiving noise signals from aggregates in the concrete, to the NF region around practically 5 mm apart from antenna, was designed. The performance of the GTSA was evaluated by a comparison with that of the TSA in the numerical simulation, and it is expected that the GTSA will be more appropriate for NF imaging than the TSA.

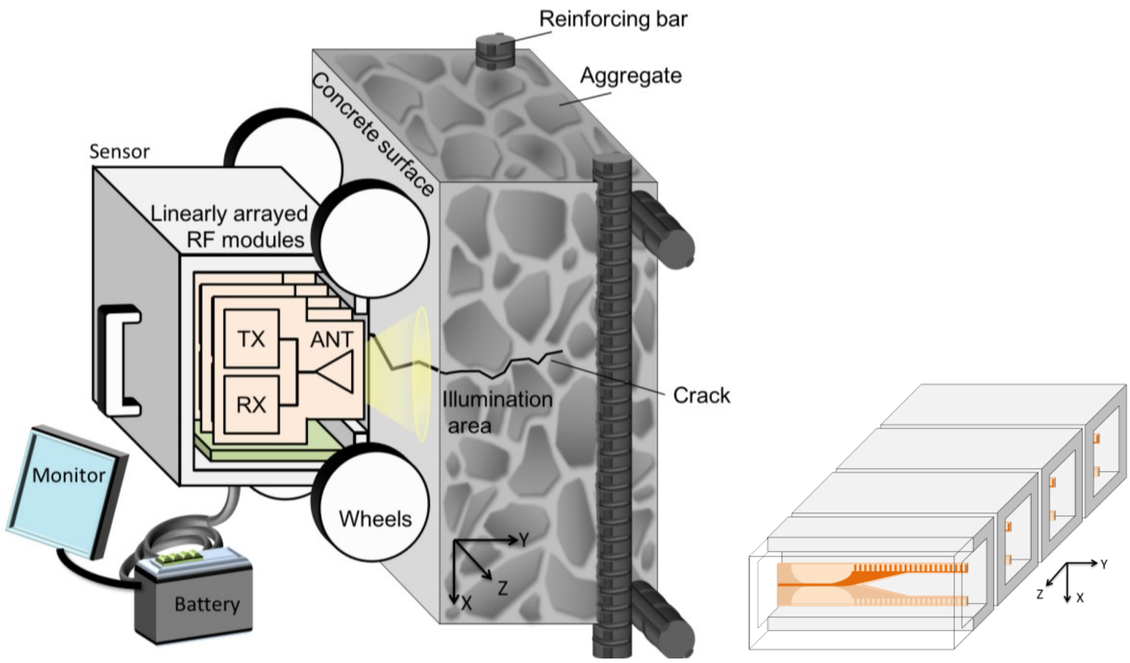
References

[1] S. Oka, H. Togo, and N. Kukutsu, ``Latest trends in millimeter-wave imaging technology,'' Proc. Progress in Electromagnetics Research Letters, vol. 1, pp. 197-204, 2008.

[2] D. M. Sheen, D. L. McMakin, and T. E. Hall, ``Three-dimensional millimeter-wave imaging for concealed weapon detection,'' IEEE Trans. Microwave Theory Tech., vol. 49, no. 9, pp. 1581-1592, Sep. 2001.

[3] S. Mochizuki, S. Oka, H. Togo, and N. Kukutsu, ``High-phase-resolution 77-GHz-band radar module for near-field millimeter-wave imaging,'' Proc. IEEE MTT-S International Microwave Symposium Digest, vol. 2, pp.793-797, 2010.

[4] R. Appleby, ``Passive millimetre-wave imaging and how it differs from terahertz imaging,'' Phil. Trans. of T. L. Soc., Vol. 362, No. 8, 379-394, Lond. A, 2003.
[5] H. Sato, K. Sawaya, K. Mizuno, J. Uemura, M. Takeda, J. Takahashi, K. Yamada, K. Morichika, T. Hasegawa, H. Hirai, H. Niikura, T. Matsuzaki, S. Kato, and J. Nakada, ``Passive millimeter-wave imaging for security and safety applications,'' Proc. SPIE 7671, 76710V (2010).



(a) System (b) Antenna of LARF module

Figure 1: Near-field imaging system for surface crack detection of concrete structures.

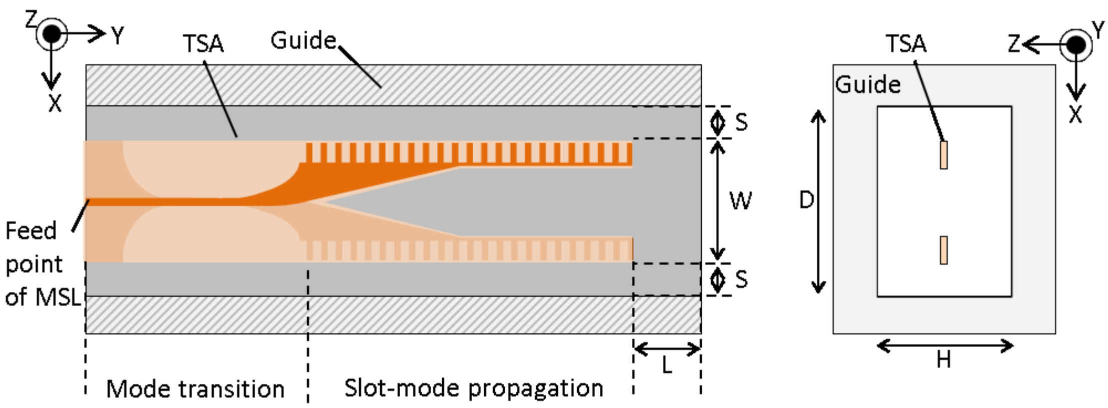
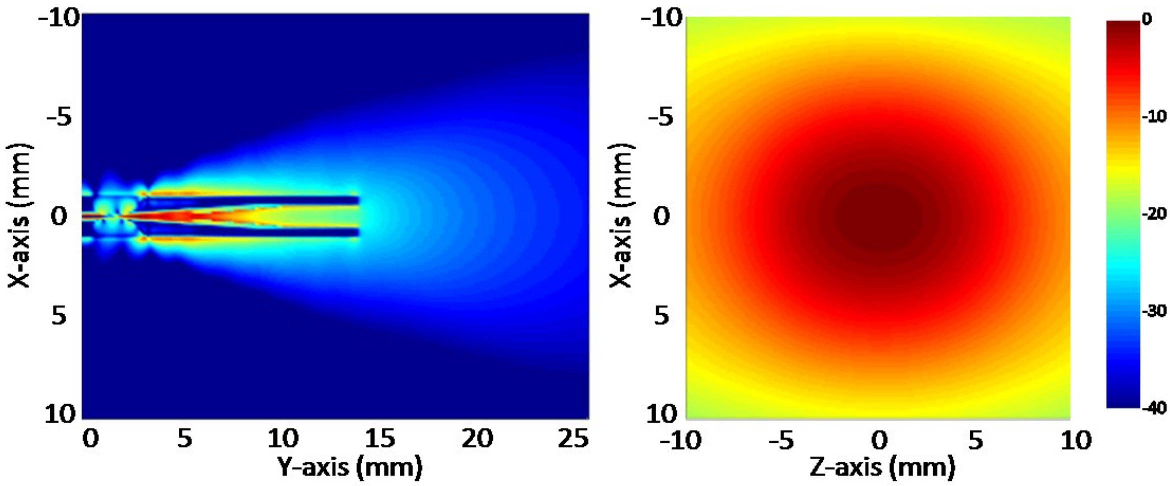
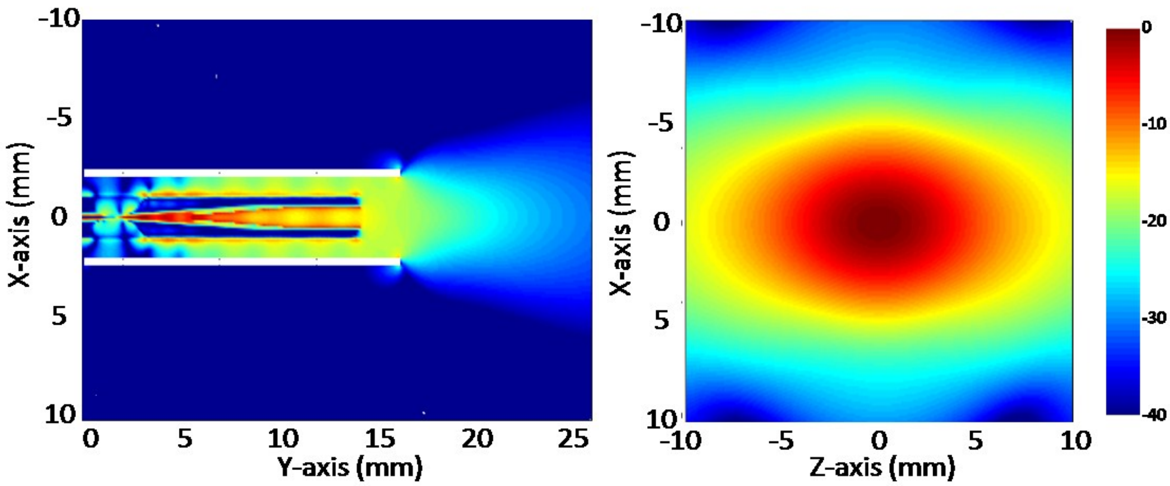


Figure 2: Configuration of guided TSA (GTSA) for near-field imaging: W is width of TSA, and L and S are length and gap between guide and TSA, respectively. Here, D and H are width and height of guide aperture.

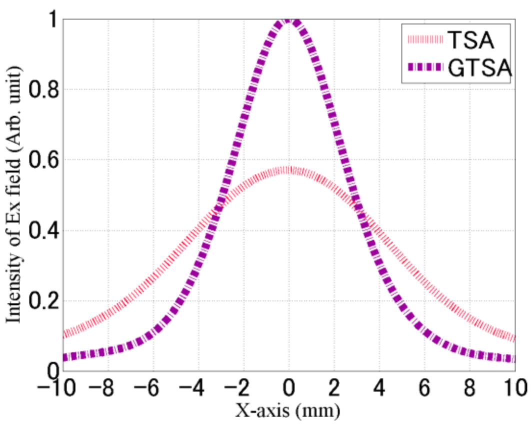


(a) TSA

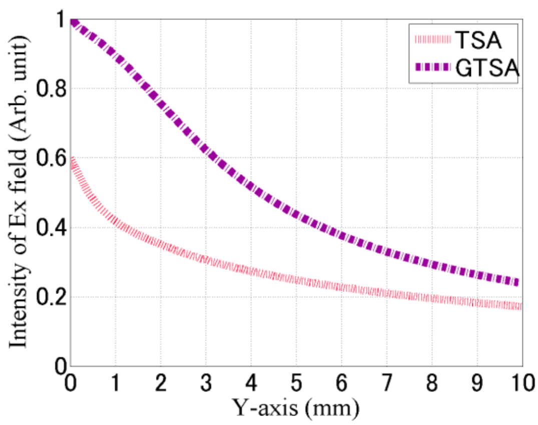


(b) GTSA

Figure 3: Calculated intensity distributions of Ex-field of TSA and GTSA on log scale: XZ-plane is at 5-mm apart from each antenna tip. Each value is normalized by peak in its plane.



(a) X-axis at 5 mm from antennas.



(b) Y-axis at center of antennas

Figure 4: Comparisons in calculated near-field between TSA and Guided TSA(GTSA).