Millimetre-wave end-fired antenna array for active 3D holographic imaging system

Weihai Fang, Peng Fei and Feng Nian

A compact Ka-band (26.5–40 GHz) dielectric rod end-fired antenna array for the three-dimensional (3D) active holographic imaging system is presented. Without horn shape feeding, the new antenna array is specially designed with characteristics such as small size, high gain, good radiation pattern, easy realisation, low insertion loss and low mutual coupling. In the imaging system, the spacing of sending and receiving antenna units is 1.5 wavelengths with mutual coupling <−30 dB and a gain of 12–16 dB. The results and analysis provide guidelines for the design of millimetre-wave end-fired antenna arrays.

Introduction: Wideband antenna arrays are of interest for various applications including active and passive holographic imaging, see-through walls and precise localisation [1, 2]. For a millimetre-wave three-dimensional (3D) holographic imaging system, the antenna array electrically scans the target to be examined in one direction. The antenna array is an end-fired antenna, which includes but is not limited to a dielectric rod antenna (DRA), a printed antenna and other tapered slot antennas. DRA arrays have numerous advantages over other end-fired antenna arrays [3, 4]. They have low insertion loss, broadband input matching high mutual decoupling efficiency and low manufacturing cost. Additionally, the radiation pattern of the DRA is almost frequency-independent.

In this Letter, a Ka-band (26.5–40 GHz) compact DRA array for the 3D holographic imaging system is presented. A DRA unit was specially designed having small size, high gain, good radiation pattern and easy realisation. The DRA unit with the WR-28 metal waveguide feeding directly formed a compact antenna array with low insertion loss and mutual coupling.

Structure and analysis: The schematic structure of the proposed DRA unit is shown in Fig. 1. The feeding section fits into the WR-28 metal waveguide, which does not require any horn structure. Using a ‘swallow-tail’ and taper structure can realise good matching. Just by changing the narrow side while with a constant broad side of the dielectric waveguide, this antenna achieves a coincidence *E*- and *H*-plane radiation pattern. Additionally, antenna units can be easily fixed in WR-28 metal waveguides identically for the antenna array.

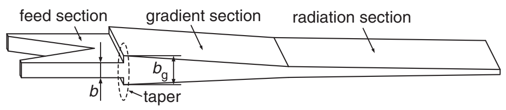

Fig. 1 *Schematic structure of DRA unit*

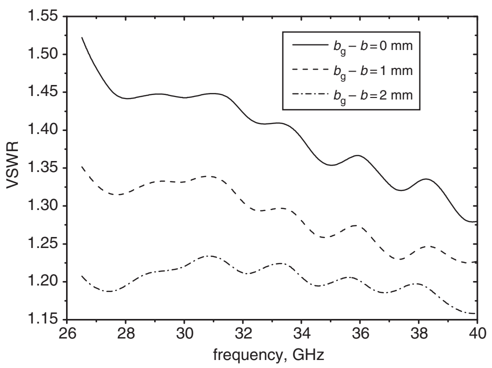

Fig. 2 *Voltage standing-wave ratios in different taper thicknesses*

The horn shape input match is a common optimised structure for a DRA. A horn antenna feed is bulky, expensive and requires larger space, leading to a large unit spacing in an array environment. In Fig. 1, a swallow-tail and taper input match instead of a horn shape is shown. The transmission mode of TE_{10} in the metal waveguide transforms to the E_{11} surface-wave mode in the dielectric rod waveguide. Good input matching needs their propagation constants to be as close together as possible and this can be achieved by optimising the thickness b_g of the taper.

The voltage standing-wave ratio (VSWR) of the DRA unit in different b_g is shown in Fig. 2, where the dielectric of teflon with the relative permittivity $\varepsilon_r = 2.1$ is chosen. Without the taper ($b_g = b$), the VSWR is about 1.45, but this is <1.25 when $\Delta = b_g - b = 2$ mm. $\Delta/2$ (i.e. 1 mm) is commonly the thickness of the standard waveguide wall. Therefore, the cross-section of the antenna is comparable to that of the WR-28 metal waveguide and this structure is more compact than any horn feeding antenna.

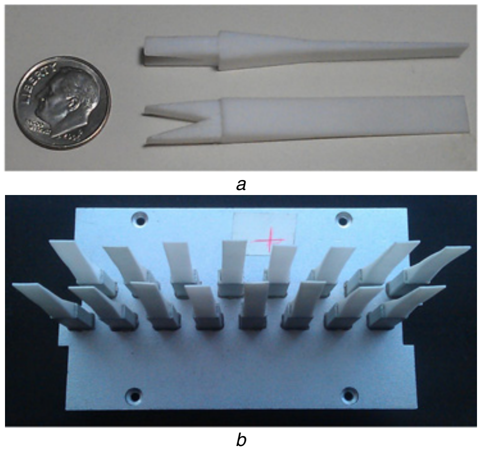

Fig. 3 *Photographs of antenna units and array*

a Antenna units made of teflon
b Module of antenna array

The radiation of the DRA antenna depends on the total effects of the feed structure and antenna together. The feed of the metal waveguide couples a portion of the input power to a surface wave, which travels along the gradient and radiation section, where it radiates into space. The ratio of the power in the surface wave to the total input power (efficiency of excitation) is usually between 65 and 75% [5]. Power not coupled to the surface wave is directly radiated by the metal waveguide in a pattern resembling that radiated by the feed when no antenna is in front of it. A double body tapering (gradient and radiation sections) is introduced in Fig. 1 to suppress the effect of feed radiation and to increase the bandwidth.

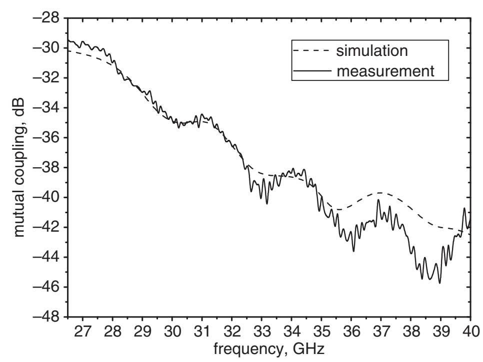

Fig. 4 *Mutual coupling of antenna array*

In an active 3D holographic imaging system, the antenna array electrically scans the target to be examined in one direction, and mechanically scans it in the other direction. It commonly has two row antenna arrays to complete the sending and the receiving signal, respectively. Photographs of our DRA unit and array module are shown in Fig. 3. DRA units directly fit into the WR-28 waveguides, which is fed by printed microstrip line probes. To obtain the best possible resolution, considering the properties of the sending and the receiving antenna, the waveguides need to be as close together as possible. Without physical interference from the waveguides, the vertical spacing of the sending and receiving antenna units is 1.5 wavelengths, whereas the horizontal spacing is 1 wavelength. The upper and lower antenna arrays are offset by a distance of 0.5 wavelengths. In a practical imaging system, the number of array modules is determined by the area to be covered.

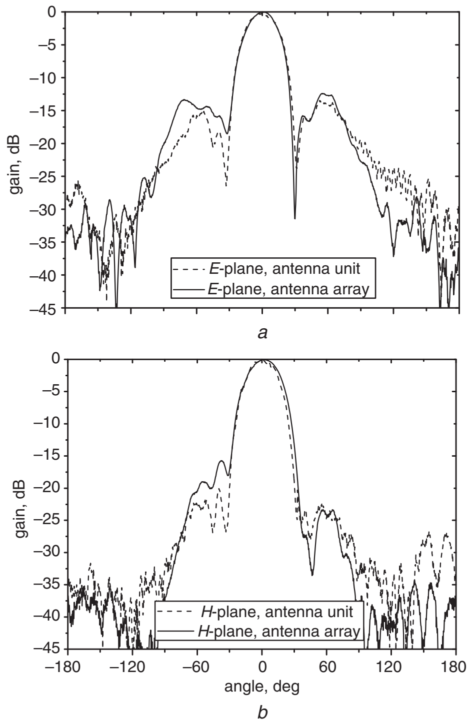

Fig. 5 *Normalised radiation patterns of antenna unit and array at 33 GHz*
a *E*-plane radiation patterns
b *H*-plane radiation patterns

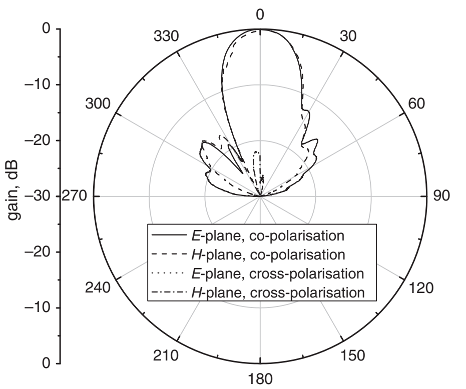

Fig. 6 *Normalised radiation patterns of antenna array at 40 GHz*

Measurement and properties: The measured properties of the antenna units and the array are shown in this Section. In an active imaging system, the mutual coupling of the nearest sending and receiving antennas affects the sensitivity and dynamic range. The mutual coupling of our DRA array is shown in Fig. 4 with compared simulation and measurement results and the maximum coupling is about −30 dB.

The beam width of the antenna array determines the lateral resolution of the imaging system. To increase the lateral resolution, the beam width range from about 10° to about 60° is preferred, and the beam width of about 40° being the most preferred.

The measured *E*- and *H*-plane radiation patterns of the antenna unit and array at 33 GHz are shown in Fig. 5. The side-lobe level of the DRA array slightly increases compared with the DRA unit. This is because of the influence of other DRA units which act as parasite units. The side-lobe level of the DRA array is < −13 dB. The cross-polarisation of the antenna array is < −20 dB in the Ka-band and Fig. 6 shows the co-polarisation and cross-polarisation of the antenna array at 40 GHz.

Conclusion: A compact DRA array for the Ka-band millimetre-wave 3D holographic imaging system is presented. In our imaging system, the spacing of the sending and receiving antenna units is 1.5 wavelengths with mutual coupling < −30 dB; the gain from 26.5 to 40 GHz is 12–16 dB from our measured results. The results and analysis in this Letter also provide guidelines for the design of antenna arrays in millimetre-wave passive imaging systems.

4 January 2014
doi: 10.1049/el.2014.0040
One or more of the Figures in this Letter are available in colour online.

Weihai Fang, Peng Fei and Feng Nian (*Science and Technology on Metrology and Calibration Laboratory, Beijing Institute of Radio Metrology and Measurement, Beijing 100854, People's Republic of China*)

E-mail: whfang@mail.ustc.edu.cn

References

1 Patrik Pousi, J., Lioubtchenko, D.V., Dudorov, S.N., and Raisanen, A.V.: 'High permittivity dielectric rod waveguide as an antenna array element for millimeter waves', *IEEE Trans. Antennas Propag.*, 2010, **58**, (3), pp. 714–719
2 Lioubtchenko, D.V., Dudorov, S.N., Mallat, J.A., and Raisanen, A.V.: 'Dielectric rod waveguide antenna for W band with good input match', *IEEE Microw. Wirel. Compon. Lett.*, 2005, **15**, (1), pp. 4–6
3 Patrovsky, A., and Wu, K.: 'Active 60 GHz front-end with integrated dielectric antenna', *Electron. Lett.*, 2009, **45**, (15), pp. 765–766
4 Kazemi, R., Fathy, A.E., and Sadeghzadeh, R.A.: 'Dielectric rod antenna array with substrate integrated waveguide planar feed network for wideband applications', *IEEE Trans. Antennas Propag.*, 2012, **60**, (3), pp. 1312–1319
5 Volakis, J.L.: 'Antenna engineering handbook' (McGraw-Hill, New York, 2007, 4th edn), Chap. 10