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Near field focusing for nondestructive microwave testing at 24 GHz – Theory and experimental verification

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ABSTRACT

This paper describes the development of different novel antenna concepts for improving the spatial resolution of microwave based non-destructive testing (NDT) at 24 GHz. In a great number of applications the antenna of the sensor can be brought very close to the device under test. In these cases, the near field characteristics of the antennas are crucial for a high resolution. However, common sensor heads offer either a high image resolution or a high penetration depth. In order to combine both of the characteristics different antenna concepts have been developed. The objectives were to obtain a high return loss combined with a sufficient high dynamic range and a near field focusing of electromagnetic waves in order to yield a high resolution. Altogether, three antennas have been set up. Each antenna has been calculated analytically, followed by a FEM simulation, near field measurements and an experimental verification.

1. Introduction

Microwave non-destructive testing is often used for the inspection of components or constructions consisting of dielectric materials. When the object is radiated with electromagnetic waves, the reflected or transmitted signal is received and processed. Most imaging methods are based on the synthetic aperture principle giving cross-range resolutions in the order of the wavelength. To improve the resolution, the radiation pattern and the near field footprint can be measured and used for the image calculation [1–3]. It is often possible to bring the sensor very close to the device under test (DUT) such that the near field characteristics of the antenna directly influence the resolution as well as the depth in which a defect can still be detected [4]. One common approach is to use open waveguides [5]. Despite the relatively low return loss, open waveguides offer moderate penetration depths of the electromagnetic waves into the DUT. That can be improved by horn antennas. However, due to the shorter distance from the phase centre to the middle of the aperture compared to the distance to the aperture edge, the horn has bad sidelobe suppression. Other options are coaxial probes that produce a small antenna footprint at short distances to the benefit of higher resolutions [6]. They are mostly used for the detection of defects near the surface. The disadvantage is that the radiated fields cannot penetrate deep enough into the DUT. This is also true for tapered waveguides with slit aperture for image contrast improvement [7] or knife blades as scanning probes at millimetre wavelengths [8]. For the same purpose, dielectric rod antennas have been optimised for spot-focusing [9].

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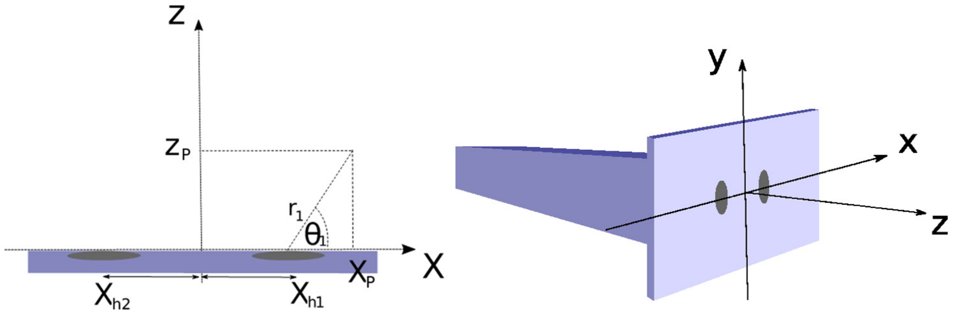

Fig. 1. Sectoral E plane horn with metal plate and holes.

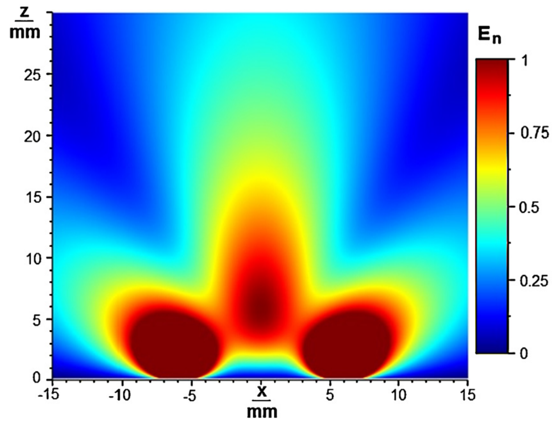

Fig. 2. Electric field distribution of two magnetic elementary antennas.

However, these antennas suffer from the drawback that only near surface defects (such as corrosion pitting under paint) can be evaluated with dielectric slab-loaded waveguides [10]. In order to facilitate deeper penetration, metal plates with defined slots or dielectric lenses in front of a waveguide were used [11,12]. This trade-off between penetration depth and spatial resolution is typical for microwave real-aperture imaging radar methods under near field conditions [13].

In this paper three improved antenna concepts were developed and their advantages and limitations compared to conventional waveguides are discussed. Especially the antenna described in the fourth section attained a 6 mm better resolution at simultaneously higher penetration depth and improved dynamic range and return loss. The greatest benefit of this concept is the independence of the focusing characteristics of permittivity of the DUT. For experimental verification of the near field characteristics of the developed antennas, the Electromagnetic Infrared method EMIR has been used [14].

2. Sectoral horn with metal plate and 2 holes

The basis of this antenna was an E plane horn for the K band with an aperture size of 20 mm × 4.3 mm. The horn aperture was covered by a metal plate with two holes as radiating elements (Fig. 1).

The holes were positioned symmetrically in relation to the centre of the wave guide such that the electromagnetic waves from both holes superimpose constructively without any phase shift along the z axis. Each hole can be modelled in good agreement with the practice by a magnetic elementary antenna (Fitzgerald dipole). The azimuth component of the electric field of radiator 1 (right hole in Fig. 1) E_φ^{h1} located at $(x, z) = (x_{h1}, 0)$ is given by

$$E_\varphi^{h1} = E_0 \cdot \frac{-e^{-j \cdot \frac{2\pi}{\lambda} \cdot r_1}}{4\pi} \cdot \left(\frac{1}{\beta \cdot r_1} + \frac{1}{j \cdot \beta^2 \cdot r_1^2} \right) \cdot \sin\theta_1 \tag{1}$$

where E_0 is a reference field strength, $r_1 = \sqrt{(x_P - x_{h1})^2 + y_P^2 + z_P^2}$ is the distance from the hole to the computation point (x_P, y_P, z_P), λ is the free-space wavelength and the θ_1 is given by the distance from the aperture to the computation point [15]. The electric field E_φ^{h2} can be obtained similarly. The resulting field is given by a superimposition of both fields.

Fig. 2 shows the magnitude of the electric field distribution for two holes with 12 mm distance to each other, normalised to the maximum electric field that occurs in vicinity of the two holes at $x = \pm 6$ mm. A second maximum occurs at $(x, z) = (0, 5\text{ mm})$ due to the equal phase superimposition of both fields. However, at a distance of $z = 10$ mm the ratio between