Millimetre Wave Frequency Scanning Probe for Imaging Applications

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***Abstract*—The use of a scanning probe for the data acquisition process in millimetre wave imaging systems enables the separation of the contributions originated by the different vertical segments of the object under investigation, providing additional information. For this purpose, a frequency scanning antenna topology contributes to reduce the complexity of the measurement equipment required, as the steering is directly controlled by the illumination frequency.**

An eight element frequency scanning antenna array operating in a 3 GHz band centred at 35 GHz is presented, providing a steering range of $\Delta\theta = 20°$. The frequency scanning behaviour has been achieved through a corporate feeding network that delivers the conveniently phase shifted input signals to the aperture coupled microstrip antennas used as individual radiators. The design has been experimentally validated through measurements of the manufactured prototype.

I. Introduction

Millimetre wave imaging techniques have recently awoken considerable interest due to their multiple applications in a wide variety of fields, such as non-destructive testing [1], detection of buried or concealed weapons [2], or objects in general [3], non-invasive diagnostics [4], etc.

The main advantage of the millimetre wave band over other regions of the spectrum, is that some materials (most common clothing items, for instance) are transparent to this kind of radiation, which is either spontaneously radiated or reflected and scattered by the objects placed underneath. This radiation can be used to compose an image that exposes internal features of the objects under screening, that are not revealed in conventional optical images.

Imaging systems can be generally classified into two different categories. Passive imaging schemes [3], [4] rely on the black body radiation theory, whereby objects at a temperature above absolute zero emit different levels of thermal radiation, depending on their temperature. The accurate acquisition of these different levels of radiation through high resolution radiometers enables the composition of an image of the scene. Active imaging systems [1], [2], on the other hand, are based on illuminating the scene with millimetre wave radiation and measuring the amount of power reflected by the different targets. Since the level of reflected power is usually substantially higher than the natural emissions used in the passive approach, the design requirements for the acquisition systems can be significantly relaxed.

For active imaging acquisition schemes, multiple types of illuminations of the object under investigation can be chosen, using single frequency [5], multi-frequency [5]–[7] or Ultra Wide Band (UWB) signals [8]. The scattered and reflected radiation is usually measured in several spatial directions (angular diversity) in order to increase the image resolution. Different measurement set-ups have been proposed, based on mechanically rotating mirrors, combined with a linear movement of the probe [1], a rotary scanner with variable radius [9], etc.

In this work, an active imaging system based on the measurement set-up shown schematically in Fig. 1 is proposed. The object under investigation is uniformly illuminated in an anechoic environment, using a mildly directive horn antenna. In order to separate the contributions of the different vertical segments of the target, the reflected power is measured using a directive probe whose main lobe can be steered in the vertical plane. The object under investigation is placed on an azimuthal positioner and progressively rotated to evaluate the response for multiple incidence angles.

Although the scanning of the probe could be achieved through the mechanical rotation of a directive antenna, or through repeating the measurements for different positions of the probe and using array synthesis techniques, the antenna array approach is generally more appropriate, as it enables agile electronically steerable implementations, which can potentially speed up the acquisition process.

Furthermore, it is usually sought to keep the measurement equipment to a minimum, which is usually a Vector Network Analyser (VNA), along with some auxiliary circuitry [7]. Thus, a receiving probe based on a frequency scanning microstrip antenna array [10], which can be directly controlled by the VNA, is an interesting option, as it provides the required steering behaviour, without further increasing the complexity

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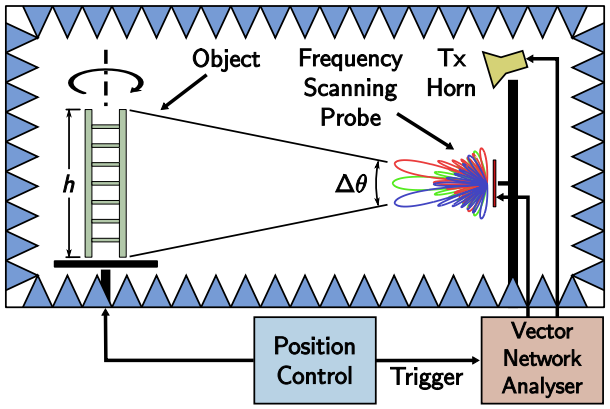

Fig. 1. Proposed measurement set-up.

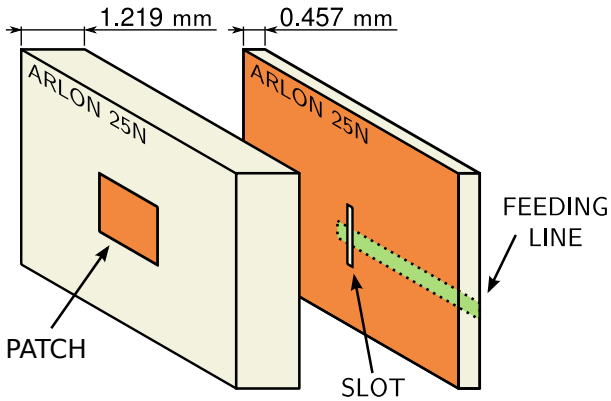

Fig. 2. Multilayer structure of the individual radiating element.

of the measurement set-up.

In the following, an eight element frequency scanning microstrip antenna array operating in a 3 GHz band centred at 35 GHz is presented, providing a steering range $\Delta\theta$ greater than 20°.

II. Radiating Element

The individual radiating element is an aperture coupled microstrip antenna, designed on a multilayer structure of the substrate ARLON 25N ($\varepsilon_r = 3.38$, $\tan\delta = 0.0025$ at 10 GHz), as shown in Fig. 2. Aperture coupling is advantageous over other feeding techniques for this kind of applications, as it minimises the impact of the spurious radiation produced by the feeding network on the antenna radiation pattern.

A rectangular patch has been structured on the top layer of a 1.219 thick ARLON 25N substrate. The patch is fed from underneath by electromagnetic coupling through a rectangular slot etched on the ground plane of the 50Ω feeding line, which has been implemented on a 0.457 thick ARLON 25N substrate layer.

The electromagnetic Method of Moments (MoM) simulation of the antenna element shows an impedance bandwidth greater than 3.5 GHz, centred at 35 GHz, which effectively covers the desired operating bandwidth of the frequency scanning probe.

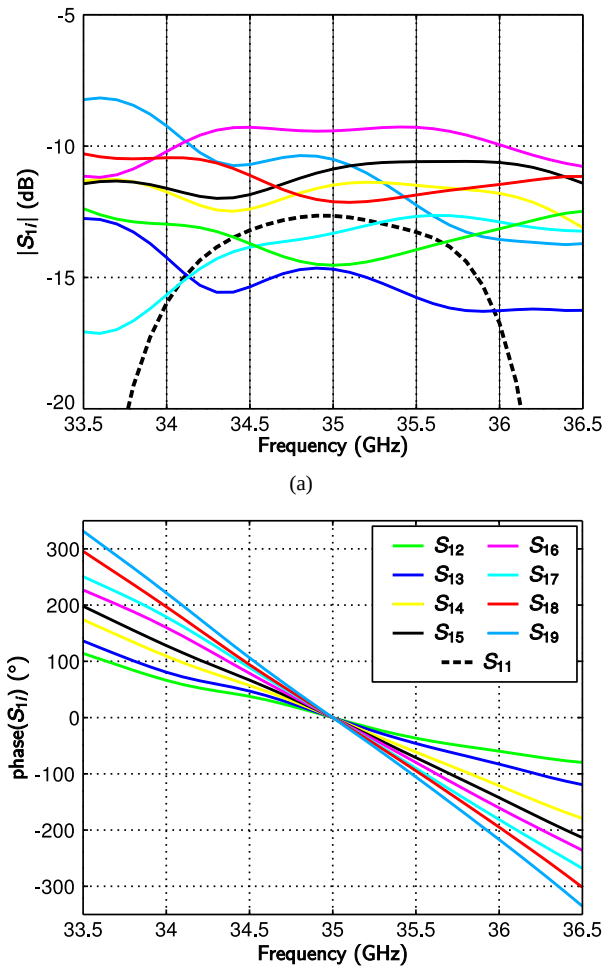

Fig. 3. Simulated scattering parameters (S_{1i}) of the feeding network (a) amplitude and (b) phase.

III. Feeding Network

The frequency scanning antenna implementation proposed in this work is based on a phased array whose radiating elements are fed through transmission line segments of different lengths. The phase shift $\Delta\phi$, undergone by an electromagnetic wave propagating through a transmission line of length L, is known to be given by:

$$\Delta\phi = -\beta L = -\frac{2\pi}{\lambda_g} L = -\frac{2\pi}{v_p} f L,$$

where f is the operating frequency and v_p de propagation velocity in the transmission line. Thus, for a fixed transmission line length L, the phase shift $\Delta\phi$ is linearly dependent on the operating frequency. For the main beam to be pointed at the boresight direction at the centre frequency $f_0 = 35$ GHz, the difference in electrical length between the feeding line of consecutive radiating elements must be an integer multiple of the guided wavelength λ_{g_0}, $\Delta L = N\lambda_{g_0}$, $N \in \mathbb{N}$. In order to achieve the required steering range of, at least, $\Delta\theta = 20°$, $N = 2$ has been chosen in this work.

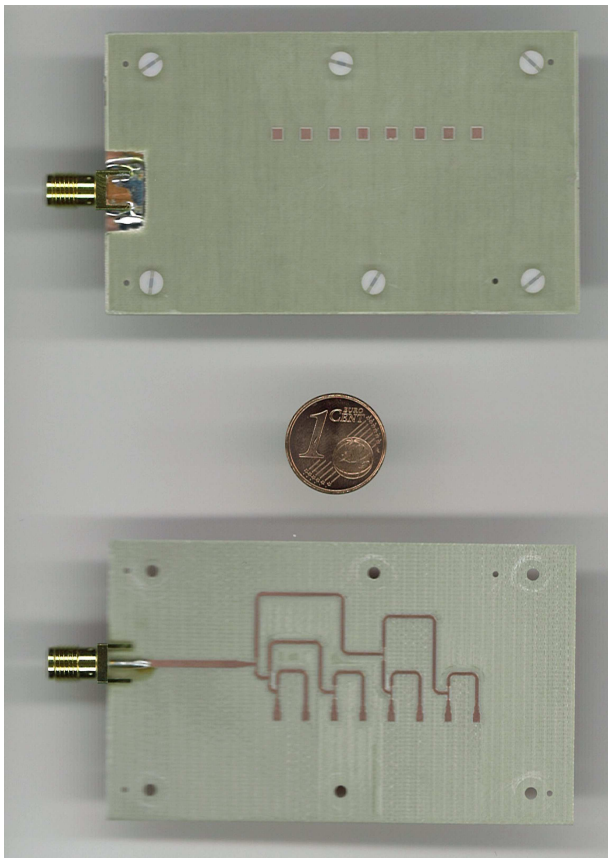

Fig. 4. Manufactured prototype of the frequency scanning antenna array: radiating elements (upper part) and feeding network (lower part).

Series feeding network topologies can lead to more compact and efficient implementations [10], although the design process is generally more complex, as it involves the simultaneous fine-tuning of all the design parameters. Parallel topologies, on the other hand, offer more flexibility and ease of design while, for arrays with a moderate number of elements, reasonably sized implementations can be obtained.

A parallel feeding network has been designed for the 8×1 antenna array. Due to its narrower width, which simplifies the layout process, a characteristic impedance of 75Ω has been chosen. The input power is successively divided through symmetric T-junction power dividers. Quarter wavelength impedance transformers have been used to match the input of the feeding network to 50Ω and the input of each of the radiating elements to 75Ω.

The simulated scattering parameters of the feeding network are shown in terms of amplitude in Fig. 3(a), and phase in Fig. 3(b). The return loss of the feeding network is over 10 dB throughout the whole band of interest. The ratio of power delivered to each of the output ports with regard to the input power shows a slight variation depending on the specific port (about 5 dB), due to the difference in the length of the transmission line segments. A progressive phase shift distribution is observed in the output ports, as a function of the frequency of operation.

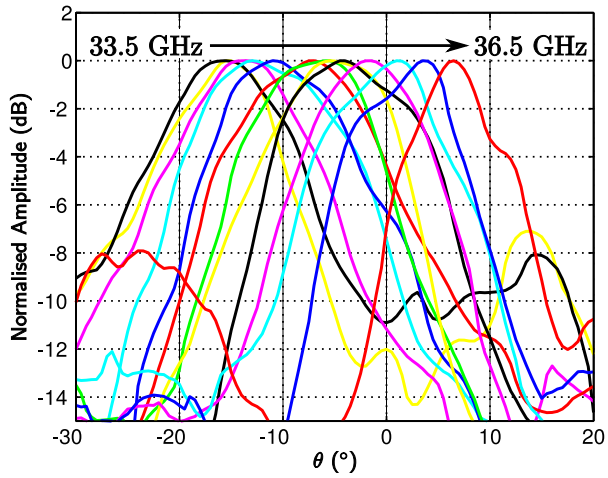

Fig. 5. Radiation patterns of the manufactured frequency scanning antenna array, measured in the anechoic chamber between 33.5 and 36.5 GHz, in steps of 0.25 GHz.

IV. Experimental Results

A prototype of the frequency scanning antenna array has been manufactured for the experimental validation of the design. The radiating patches are shown on the upper part of Fig. 4 and the feeding network on the lower part. The complete multilayer structure has been assembled using nylon screws.

The normalised radiation patterns measured in the anechoic chamber at frequencies between 33.5 and 36.5 GHz in steps of 0.25 GHz are shown in Fig. 5. The main lobe can be steered in the range $\theta \in [-15.5°, 6.5°]$. The secondary lobes are below -8 dB in the region of interest, for all the operating frequencies considered. The required scanning range $\Delta\theta = 20°$ has been successfully attained in the band between 33.5 and 36.5 GHz.

V. Conclusion

A frequency scanning antenna array has been proposed to simplify the data acquisition process in millimetre wave imaging schemes. In order to introduce a frequency scanning probe for the data acquisition process in millimetre wave imaging systems, a frequency steering microstrip antenna array operating from 33.5 to 36.5 GHz has been proposed. Aperture coupled microstrip antennas have been used as individual radiators, in order to minimise the detrimental influence of the spurious radiation produced by the feeding network on the radiation pattern. The design has been validated through measurements in the anechoic chamber, obtaining a scanning range $\Delta\theta = 20°$, with a secondary lobe level under 8 dB.

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