Millimetre-wave active integrated antennas with electromagnetic band-gap (EBG) superstrate lens

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1. Introduction

This paper presents a study of millimetre-wave active integrated antennas (AIAs) for imaging applications. The aim of this research work was firstly to develop an in-house FD-TD code that can accurately model these antennas and secondly to investigate how they can be successfully included in a tightly packed millimetre-wave imaging array (IA). The chosen antenna element is a slot-ring antenna operating at around 90 GHz. The active element integrated with the slot-ring is a Schottky diode. The integrated configuration forms a compact millimetre-wave receiver. It operates dually as an antenna and a quasi-optical mixer and hence it can form the basic element of a millimetre-wave IA. Although substrate lenses have been previously used to alleviate surface-wave coupling phenomena, in this work the lenses were replaced by Electromagnetic Band Gap structures (EBGs). The passive designs were simulated by CST Microwave Studio ™ and the active designs by a customized in-house FD-TD code in Fortran 90.

2. FD-TD Modelling

A successful CAD should be able to handle the non-linearities of the active elements as well as the radiation from the antennas and any emitted from the associated circuitry. Conventional circuit analysis packages cannot be relied upon for the analysis of the active elements as their equivalent circuits approach cannot handle the complex radiation [1]. An in house FD-TD code has been developed and various FD-TD algorithms were implemented so that the millimetre-wave active slot-rings can be modelled as accurately as possible. FD-TD can be used to successfully model complicated antenna structures and circuits that include both linear and non-linear lumped elements [2]. The NL^2N algorithm was also included in the in-house code specifically for the purposes of modelling packaged Schottky diodes [3]. It enables the programmer to place both the Schottky junction and the equivalent circuit in a single cell. This way, the spectral power quantities can be extracted and the FD-TD code can provide estimates of the conversion loss of the mixer.

3. Single element quasi-optical mixer

The first resonance of the slot-ring occurs when its mean circumference equals one guided wavelength [4]. As the slot-ring will be used as a quasi-optical mixer (fig.1), it is important to add a filter that isolates the IF extraction port from both the LO and RF signals. The RF is at 90 GHz and the LO at 91.4GHz thus yielding an IF of 1.4GHz. A virtual short exists along the y-axis as the horizontal E-field components are of opposite phase and consequently cancel out (fig.3). The vertical components of the E-field along the x-axis remain aligned and the slot-ring hence exhibits vertical polarisation.

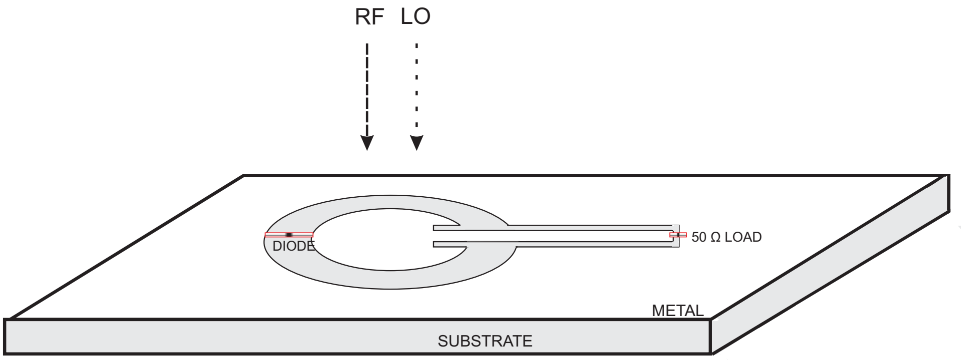

Figure 1: 90GHz compact AIA: functions as quasi-optical mixer at point B with co-planar IF extraction at point A.

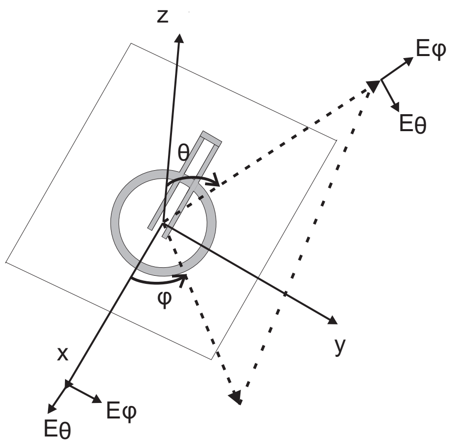

Figure 2: Coordinate system used for the pattern cuts of the planar slot-ring antenna.

4. Effects of the EBG superstrate lens

Electromagnetic Band-gap (EBG) materials are periodic structures capable of prohibiting electromagnetic (EM) wave propagation within a certain frequency band for certain arrival angles and polarisations. When an EBG structure is placed on top of a planar antenna in the form of a superstrate, the separation between them results in a cavity.

This cavity can be considered to be formed by the image of the woodpile EBG below the PEC ground plane of the planar antenna. This cavity effectively stops the periodicity of the EBG that lies above it and operates as a defect. The resonance frequency of the cavity is referred to as the defect frequency and appears as a frequency window within the stop-band provided by the EBG. The EBG structure is illuminated by the EM fields being radiated from the antenna. At this specific defect frequency, the superstrate alters the EM field distribution thus increasing the effective aperture of the antenna. All of the dielectric or metallic elements that comprise the defects of the EBG are then excited and then act as an aperture antenna.

This is how the EBG superstrate controls the distribution of the EM fields and the spatial distributions of their phases. This leads to a considerable enhancement of the radiation pattern. In EBG superstrate lenses, there is no focal region that the array needs to be confined to, as this type of lens is effectively a planar lens with no transverse directional limit. This is in contrast to a conventional elliptically shaped dielectric lens (fig.4). This offers the advantages of volume reduction and flexibility in use along with improved beam-shaping capabilities.

The woodpile EBG structure was chosen for this work. It was placed above both the metal side (fig.5) and the substrate side (fig.6) which is the direction of maximum radiation. The distance between the antenna's surfaces was expressed in terms of the free-space wavelength λ =3.33mm (lamda). When the EBG lens was placed above the metallization, the maximum directivity was 4.55dBi and it was obtained at a distance $\lambda_0/2$. This topology produced a 12.9dBi improvement over the original design.

When the lens was placed above the substrate, the maximum directivity was 9.06dBi at a distance $\lambda_{0,}$ which is a 4.43 dBi improvement over the original case. A 2-by-2 array was also designed. The slot-rings were at a distance of 1 $\lambda_{g,}$, where λ_g is the guided wavelength in Si (0.974mm) . For this array, the superstrate EBG lens was placed $1\lambda_0$ above the substrate side. The EBG lens improved the directivity by 10 dBi (fig.7). The active array was simulated with the in-house FD-TD code and it was found that the EBG lens additionally increased the extracted IF levels.

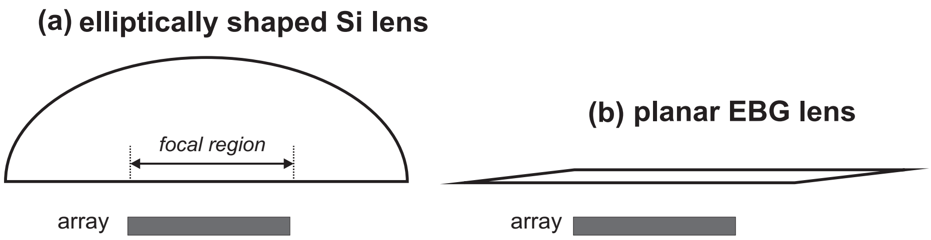

Figure 3: Transverse size comparison between elliptically shaped dielectric and planar EBG lenses.

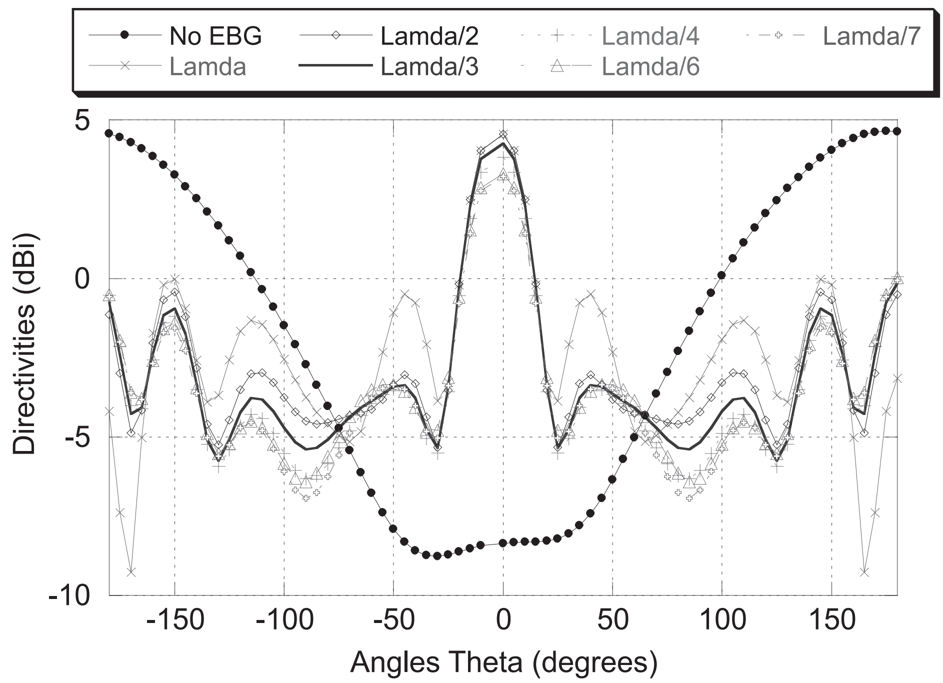

Figure 4: Variation of directivity obtained depending on the distance between the EBG lens and the metal plate of the slot-ring.

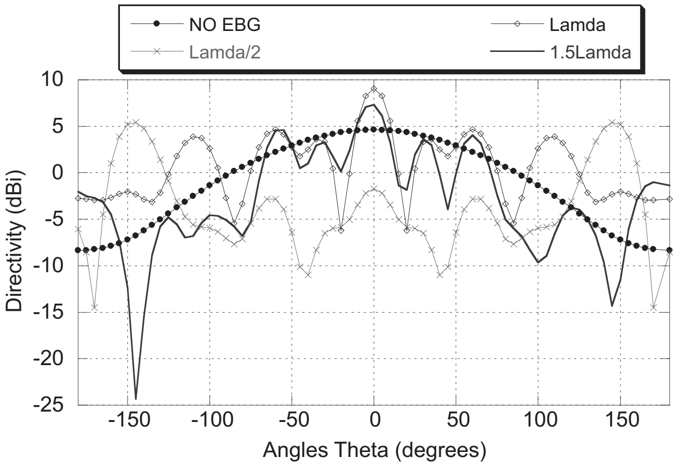

Figure 5: Variation of directivity obtained depending on the distance between the EBG lens and the substrate of the slot-ring.

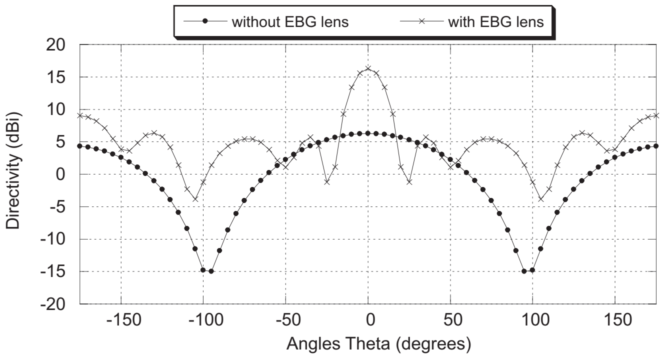

Figure 6: Comparison of the directivity obtained from a 2-by-2 slot-ring array with and without the use of the superstrate lens.

5. Conclusions

This work concerned the operational enhancement of millimetre-wave AIAs by means of using novel EBG superstrate lenses instead of the conventional dielectric ones. The active versions of the designs were simulated by an in-house FD-TD code that allowed estimation for the mixer performance. More details concerning the designs and simulations and further results will be presented in the session.

References

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