Metamaterial application in active millimeter wave imaging

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The array of multiple quasi-coherent millimeter wave (mm-wave) sources can reduce speckle by destroying coherence and is only effective when a very large surface (typically 1.5m by 1.5m) is filled with thousands of expensive mm-wave sources. This virtually exists till to now in the mm-wave range as it is unexpectedly expensive. Angle diversity technique using multiple antenna beams to receive multipath signals arriving at different angles can be used to reduce speckle. In this work such multi beam array is realized by using a single mm-wave source , Back Wave tube Oscillator(BWO) and a meta-material array where each element functions like a digital 'ON' & 'OFF' switch by changing frequency.

Introduction

Metamaterials are artificial materials (i.e., $\boldsymbol{\varepsilon} < 0$ and /or $\boldsymbol{\mu} < 0$) that exhibit electromagnetic responses generally not found in nature [1]. These materials usually gain their properties from structure rather than composition [1, 2, 3]. The primary area of research in metamaterials is investigation of materials with a negative refractive index. The potential ability to engineer the electromagnetic responses of materials for a wide variety of applications has stimulated significant interest in metamaterials. The potential applications are diverse[4] and include remote aerospace applications, sensor detection[5] and infrastructure monitoring, public safety[5], high-frequency battlefield communication and lenses for high-gain antennas etc. In this paper we will report the possibility to use metamaterial as a novel diffuser system to reduce speckle of millimeter wave (mm-wave) active imaging.

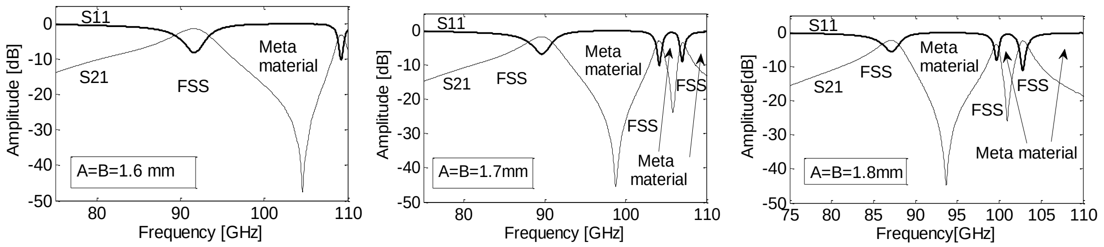
In the mm-wave range mainly coherent "laser-type" sources are available, which leads poor image quality, due to the noise artifacts like speckle, glint, and ringing [6]. The destruction of the coherent level is a prerequisite to obtain sufficient image quality. Angle diversity is a technique using multiple antenna beams to receive multipath signals arriving at different angles to reduce mm-wave speckle [6]. The method for destroying coherence requires a very large array filled with thousands of expensive mm-wave sources and to switch the sources in a fully electronically controllable random fashion. This system virtually exists till to now in the mm-wave range as it is unexpectedly expensive. An alternative way can be a large antenna array of multiple quasi-coherent sub-arrays with a discrete fashion where the transmission from the sub-arrays reaches to the object with different angle. We propose the sub-array elements as metamaterial and by changing the incident frequency of the tunable BWO 'ON' & 'OFF' controllability can be achieved.

Metamaterial characterization

Slot FSS as Metamaterial

Frequency Selective Surface is a kind of equivalent LC resonator. Bellow resonant its impedance is inductive and above resonant it is capacitive. The resonant frequency and bandwidth of slot FSS depends on slot dimensions, the unit cell dimension (e.g. periodicity) and the dielectric thickness [7]. If the dimensions of the unit cell are λ/2 or less the structure behave as FSS filter (i.e. with positive reflective index). If the unit cell or the periodicity is greater than λ/2 the higher order modes introduces.. The structure shows metamaterial behavior in some frequency range between the first and the second resonances, the second and the third resonances and so on as shown in Fig.1.

To investigate the metamaterial behaviors the simulations of the slot FSS were carried out for the unit cell dimensions values of 16mm, 1.7mm and 1.8 mm considering the infinite boundary conditions. When inter-elemtne spacing of the slot FSS is 1.6mm (Fig.1(a))the first resonance apperas at 91.7GHz and the second resonance at 109.2 GHz. If we observed the S11 and S21 curves we can see that within 93.5 GHz to 108.8 GHz the S11 and S21 curves reverses. So within these frequency ranges the structure behaves as meta material or left handed material. A further increase the inter-element spacing to 1.7mm introduces first, second and the third resonances at 89.67GHz, 104.3GHz and 107 GHz respectively. In this case the metamaterial regions occurs between 91 GHz to 103.7GHz, 104.6GHz to 106.7GHz and above 107.5 GHz as shown in Fig. 1(b). When the interelement spaing is 1.8mm the first, second and the third resonances occurs at 87GHz, 99.71GHz and 102.8Ghz rerspectively as shown in Fig.1(c). Now the structure shows the metamaterial range from 88GHz to 99 GHz, 100GHz to 102 GHz and above 103 GHz.



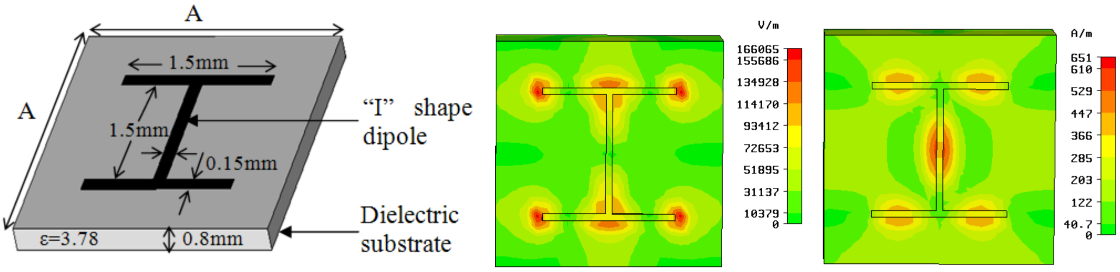
(a) (b) (c)

Fig.1: CST simulation of slot FSS as metamaterial.(slot dimension where the slot 1080 µm × 50 µm, dielectric (Quartz)thickness 800 µm and the thickness of Aluminum is 5 µm)

So the conclusion is by changing the unit cell dimension the metamaterial range can be changed and the structure shows narrow band meatmaterial behaviour for higher order modes.

Narrow Band Metamaterial

The bandwidth of FSS depends on the inter-element spacing i.e. the periodicity. Higher the value of periodicity lower is the bandwidth. This tricks is applied in this design to get very narrow band metamaterial characteristic from an “I” shape dipole FSS of periodicity greater than λ/2. The structure is simulated for the cell dimension of A1=2.35 mm , A2=2.35 mm , and A3=2.35 mm. The following Fig.3 shows the narrowband metamaterial characteristic of the structure at different frequency with change of parameter value “A”.



(a) (b) (c)

Fig.2: Unit cell layout of "I"shape dipole FSS with unit cell dimensions greater than λ/2: (a) Unit cell configuration (b) the electric field distribution and (c) the magnetic field distribution of the dipole at 99.78GHz.

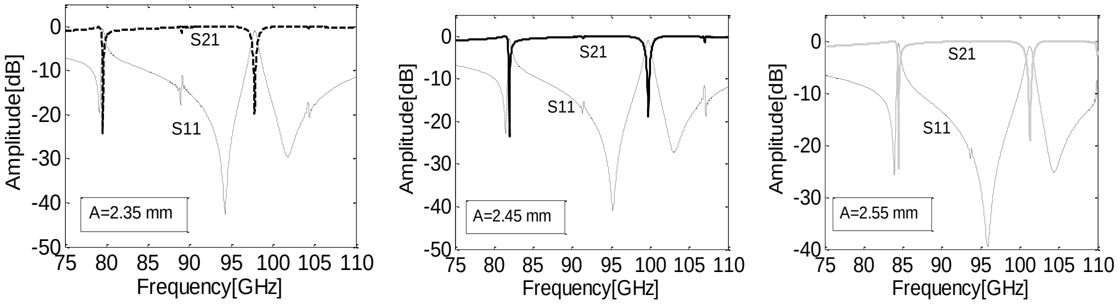


Fig. 3 Narrow band metamaterial characterization : (a) ,(b) and (c) show the narrow band metamaterial characterization of the structure near (78.58 GHz and 97.82 GHz), (81.97 GHz and 99.78 GHz), and (84.48 GHz and 101.3 GHz) respectively.

Modelling of the diffuser

The construction of such a novel diffuser array with Meta material is shown in Fig.4 (a).It is very important to make the diffuser in a way that the transmitted beam towards the object will make different angle. Obviously if the array size is big enough and if only selected portions of the array at a particular frequency transmits and the rest of the part of the array blocks the illumination the object and the rest of the part of array surface behaves as absorber then the total effect will be to illuminate the object with some beam of different angle.Improvement of speckling noise is discussed in which a central light beam is divided into a plurality of sub-beams.

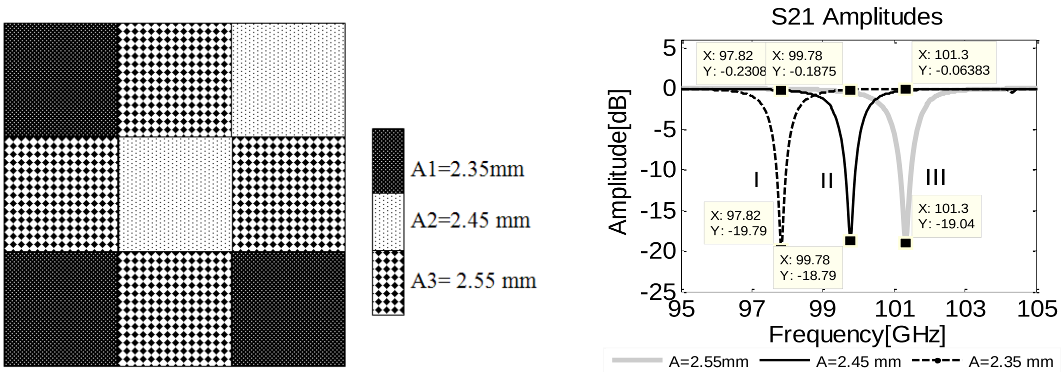


Fig.4: The construction of a novel diffuser with Meta material: (a) Schematic diagram and (b) the S21 amplitudes of the sub-arrays of the diffuser.

The S21 parameters of diffuser elementary cells are shown in Fig.4 (b). For curve (I) the unit cell dimention is 2.35 mm and it resonates at 97.82GHz . So at 97.82 GHz curve (I) shows -19.79dB amplitude (almost zero or “OFF”) and the curve (II) and (III) show -0.0566dB (almost 0 dB, or “ON”).For curve (II) the unit cell dimention is 2.45 mm and it resonates at 99.78 GHz. So at 99.78 GHz FSS (II) shows -18.79dB amplitude (almost zero or “OFF”) and the curve (I) and (III) show -0.1875dB (almost 0 dB, or “ON”).Similarly curve (III) is with the unit cell dimention of 2.55 mm and it resonates at 101.3 GHz. Hence, at 101.3 GHz FSS (III) shows -19.04dB amplitude (“OFF”) and the curve (I) and (II) show -0.2646dB (0 dB, or “ON”). Form the above results it is seen that at each resonant frequency two of the cells behaves like switch “ON” and the other cell behaves like switch “OFF”.

Conclusion

This study aimed to design diffuser array used to reduce speckle by applying the angle diversity method. The array is proposed with FSS designed for narrow band metamaterial. The metamaterial cell behaves as “ON” or “OFF” switch at a particular frequency depending on its unit cell dimensions. A diffuser array is modeled where the sub-arrays of the array are with FSS of different cell dimensions and at the same time they are arranged in a way that the transmission from each “ON” state sub-array illuminated the object with different angle. The change of incident frequency reshuffles the “ON” and “OFF” sub-arrays. As a result the object will see a different illumination angle from the different sub-arrays at each frequency. As we use the tunable W-band tunable BWO the diffuser array can be used an mm-wave multisource. With the single BWO multi angle illuminate with large angle is not possible. For glint reduction local amplitude modulation is needed where this array is also applicable. By changing illumination frequency modulated location can be change. Hence it can be beneficial to reduce the glint if position of the glint on the image is known.

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