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Improvement of Planar Antenna Efficiency When Integrated With a Millimetre-Wave Photonic Crystal

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Abstract: In this work a coplanar waveguide (CPW)-fed slot dipole antenna has been integrated with a three-dimensional woodpile photonic bandgap crystal (PBG) in the W-band regime (67-110GHz) using silicon. A slot dipole antenna has been designed and tested at 94GHz which exhibits very poor efficiency and has high levels of loss through the back of the substrate. This integration has shown a large positional dependence of the antenna with respect to the layers of the PBG and has led to the optimisation of a slot dipole antenna on the PBG. This type of integration has shown experimentally that the overall operation of an antenna can be greatly improved due to the reflective properties of the PBG.

Introduction: Previous investigations of the integration of a planar antenna and a photonic bandgap (PBG) structure have shown that the overall characteristics of an inefficient, lossy antenna can be improved by the reflective characteristics of the PBG [1]. This improvement exhibits a stronger airside radiated power and uniformity, while it has also been shown that there is a strong positional dependence of the radiating antenna with respect to the PBG due to the change in electromagnetic environment. In this work a slot dipole antenna fed by coplanar waveguide operating at 94GHz is used to investigate this positional dependence and improvement in performance. This device is used due to the fact that when fabricated on a thin silicon membrane in the millimetre wave regime, there exists a large loss in radiation from the bottom of the substrate. Therefore when the device is mounted on the PBG this previously spurious radiation is reflected, and as a consequence is redirected to improve the overall radiated pattern from the antenna. As this type of antenna is generally used for sensing applications in low power environments, the need to improve the efficiency of the radiation is essential, such that this type of integration may be used to improve the overall situation.

Slot Dipole Antenna: The slot dipole antenna is a relatively straightforward electromagnetic structure. One of the other major advantages of this device is that it has one major radiating slot opposed to the complimentary stripline dipole. The ratio of radiation from a slot dipole operating on silicon can be represented analytically by $\varepsilon^{3/2}$ meaning that around 40% of the radiated power is lost into the substrate. The structure is fed by coplanar waveguide (CPW), which is used as it has low radiation loss and is easily integrated with peripheral devices in a MMMIC transceiver system. CPW operates using quasi-static TEM propagation, as due to the nature of the dielectric a wave travelling along CPW cannot be purely TEM. However at higher frequencies such as in the W-Band, higher order modes can be supported although the propagation characteristics become more like TE. This field configuration then must be taken into account when designing the integration of CPW with a radiating slot, as the slot supports only non-TEM propagation.

The slot dipole antenna operates in a complimentary manner to the typical stripline method. The case being here that the fields are interchanged meaning that the dominant field propagating is magnetic. To begin the design the configuration of the feeding CPW is required to give an impedance of 50Ω, to match the system impedance. This is achieved by having a central conductor width of 23μm and a ground-to-ground separation of 50μm, when fabricated on 100μm thick silicon. Through experimental measurement the optimum length of the slot for operation at 94GHz was found to be 923μm and a width of 323μm to match the input impedance.

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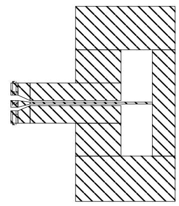
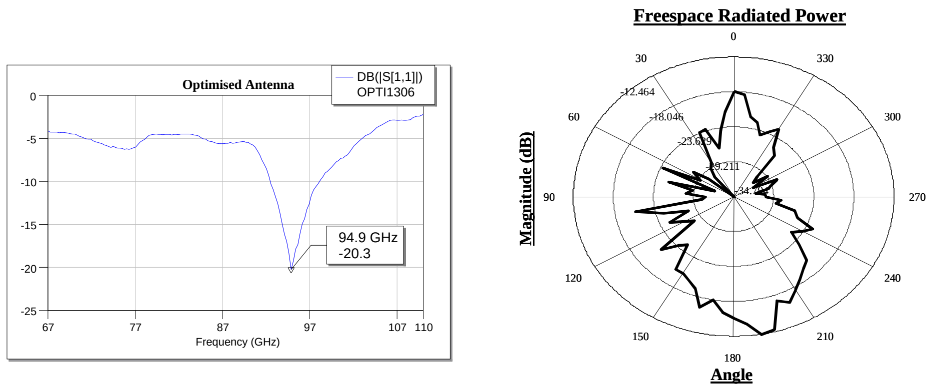


Figure 1: Schematic of Slot Dipole Antenna

The measured return loss of the slot dipole measured in freespace showed correct operation of the device at 94GHz and an acceptable magnitude of –20.3dB as *figure 2* shows:



(a) **(b)**

Figure 2: (a) Freespace return loss of device (b) Freespace Radiation of device

The frequency bandwidth (FBW) calculated for the antenna is 11.6%, showing that the antenna has a reasonably low Q factor and indicates that the impedance matching could be slightly improved, although for this integration this type of response indicates that the device is acceptable for integration.

The measurement of radiation is achieved by using a novel system and allows measurement of radiation at 5^o intervals. The power source used to drive the device is a Gunn Oscillator which is mechanically tuneable at 94GHz. Sweeps of the radiated pattern are taken in co-polarisation (H-plane) and show a very inefficient antenna with a great deal of power being radiated from beneath the substrate.

On observation of *figure 2(b)*, the magnitude of radiated power from beneath the substrate is approximately double that of the topside pattern. This shows that the antenna is very inefficient, and hence for any power dependent systems this level of performance is not acceptable. Further analysis of the result shows that the half-power beamwidth is 25 degrees and exhibits a numerical efficiency of 15.27%. This low level of efficiency, which is mainly caused by the high levels of loss through the substrate, indicates that this type of antenna is suitable for integration with the PBG which is theoretically known to improve the performance.

PBG Structure: The main attraction of a photonic crystal in the woodpile configuration is that it is easily scalable with frequency. In addition, a three dimensional crystal can be created by rotating subsequent layers in a two dimensional structure to give a face-centre-tetragonal (FCT) lattice which produces a three-dimensional bandgap [2]. The structure is formed from high resistivity silicon rods all at a rotation of 90^0 and shifted by a half-wavelength with respect to the previous layer. The dielectric difference that creates the PBG characteristics is formed by the interaction of silicon (11.7) and air (1). This woodpile structure has a large stopband of over 30GHz spanning most of the W-band range, and hence prevents any propagating electromagnetic wave passing through the crystal. This is due to the fact that in the z-direction both transverse electric (TE) and transverse magnetic (TM) modes are degenerate. The dimensions of the crystal are derived from a known crystal fabricated on alumina at 12GHz, the change of dielectric and frequency of operation are taken into account giving the geometry of the silicon rods to be 340μm with a period of 1300μm for a substrate of 380μm thickness. The PBG structure was fabricated using dry etching techniques, whereby a polymer resist mask was patterned using photolithography and was subsequently etched using inductively coupled plasma (ICP) etching. The opened windows in the resist coating are attacked using two gases etchant and passivation, defining the silicon rods and correct spacing with high resolution (*figure 3)*. This method was used to fabricate the PBG as in comparison to the already known method of wet-etching [3], as this process is more controllable. A standardised etch rate of 2μm/min is achieved with dry etch.

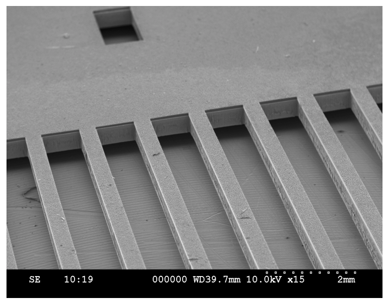
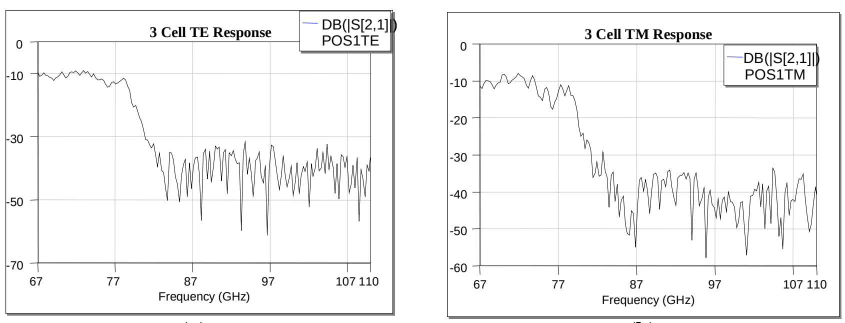


Figure 3: SEM Image of Dry Etched Silicon PBG Wafer

To confirm the presence of a stopband in the crystal, the transmission and reflection of a W-band electromagnetic signal is measured when directed at the crystal using transmitting and receiving horns. It has been found that a structure of three periodic cells (12 layers) gives an adequate stopband in both TE and TM configurations.



(a) **(b)**

Figure 4: (a) TE Response of 3 Cell Crystal (b) TM Response of 3 Cell Crystal

PBG/Antenna Integration: To gain an insight into the effect the PBG has on the resonant frequency of the antenna the return loss of the device is measured. Since the crystal is orientation dependent there are eight alignment possibilities from the two crystal positions. In the TM configuration, the rods of the PBG are situated horizontally to the antenna, and in TE the rods are situated vertically. In each of the crystal orientations there are four separate antenna alignment possibilities. In the TM configuration, the slot of the antenna can be aligned to the rod or gaps of layer 1, while the feeding CPW can be aligned to the rod or gap of layer 2. In the TE configuration, the CPW is aligned to the layer 1 rod or gaps, and the slot is aligned to either the layer 2 rod or gap. These alignment possibilities change the electromagnetic environment surrounding the antenna, and hence change the overall operation, thus measurements of the 94GHz radiating devices shown previously are performed. These measurements therefore yielded a uniform set of frequency shift values due to position. To demonstrate this uniformity, a slot dipole antenna operating at 100GHz in freespace and geometrically identical to the 94GHz device shown previously with the exception of a 50μm reduction in the length of the slot, is aligned to the PBG to utilise a -6GHz frequency shift and the radiation is then measured at 94GHz.

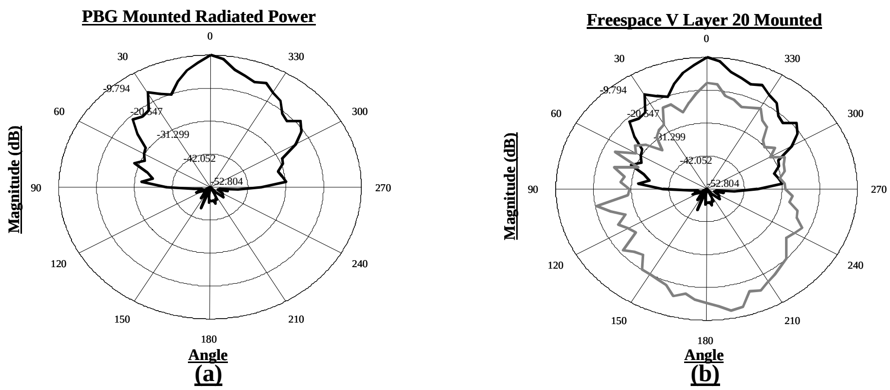


Figure 6: Comparison of Radiation Patterns (a) PBG Mounted (b) Freespace and PBG Mounted (Freespace=Grey, PBG Mounted =Black)

The power from the PBG mounted antenna exhibits significant improvement showing around double the airside magnitude. The other significant finding is that the underside radiation previously exhibited has been removed with the addition of the PBG, meaning this spurious power has been absorbed by the crystal meanwhile this spurious radiation has also been reflected to increase the airside pattern achieving a stronger airside pattern. The antenna has also become more directional and has a HPBW of 30 degrees, which is an increase of 5 degrees to the freespace version. The calculated efficiency of the antenna is then 24.7%, which shows an increase of around 10%, due to the presence of the PBG. It has also been observed that the optimum performance of the antenna is observed when mounted on a PBG consisting of only completed periodic cells. In adding even one single layer to a completed periodic cell (4 layers) there is a power drop of around 5dB in performance (*Figure 7*). This indicates that the overall antenna performance can be significantly changed due to the periodicity of the PBG structure. This phenomenon is observed to be cyclic in nature and continues to be apparent even when the PBG thickness reaches 5 periodic cells (20 layers). This observation has never before been published.

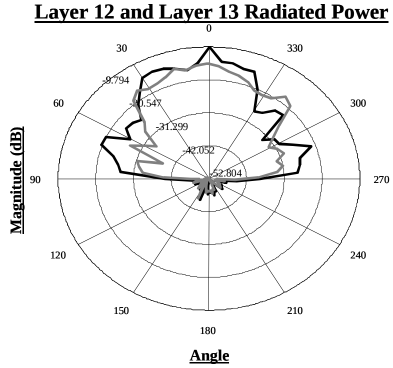


Figure 7: Cyclic Radiation change: Completed Cell (Black), Completed Cell +1 (Grey)

Conclusion: The described work presents an optimised slot dipole antenna operating at 94GHz in freespace, which shows a high level of loss. Integrating this antenna with a photonic crystal, the experimental measurements show a large positional dependence of the antenna with respect to the crystal and have given standard frequency shift and magnitude changes. This characterisation has led to the optimisation of an integrated antenna and the measured characteristics of this device show the positive effect of the crystal and an increase in efficiency which has not been observed previously. A cyclic power response has been observed which aids in defining the characteristics of this type of integration.

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[2] E. Ozbay, E. Michel, G. Tuttle, R. Biswas, M. Sigalas, K. M. Ho, Applied Physics Letters, Vol 67, April 1994
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