(Sub)mm-Wave Components and Subsystems based on PBG Technology

I. Ederra[(1)], R. Gonzalo[(1)], Chris Mann[(2)], and P. de Maagt[(3)]

[(1)] *Electrical and Electronic Engineering Department, Universidad Pública de Navarra, Campus Arrosadia, E-31006, Pamplona, Navarra, Spain*

[(2)] *StarTiger Group, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 OQX, England*

[(3)] *Electromagnetics Division, European Space Research and Technology Centre, ESTEC, PO Box 299, 2201 AG Noordwijk, The Netherlands.*

Abstract

PBG materials present some interesting properties that may overcome some of the problems of conventional technologies. In particular, PBG architecture provides a practical method for the assembly of RF circuitry having three-dimensional properties. This paper presents some (sub)mm-wave components based on this technology. PBG dipole antennas and PBG waveguides have been studied. In addition, PBG crystals and active devices have been combined for the first time resulting in a PBG mixer. First results suggest that circuits implementing PBG technology can compete with conventional waveguide technology. A PBG based subharmonic mixer operating around 250GHz exhibits a double sideband noise temperature of 3800K.

Introduction

Photonic BandGap (PBG) materials are one of the most rapidly advancing sectors in the electromagnetic arena. By using these materials, also known as Photonic Crystals (PC's), the propagation of electromagnetic waves can be manipulated to an extent that was not possible previously. These structures can prevent the propagation of electromagnetic radiation in 1, 2 or 3 dimensional spatial directions the order of which usually corresponds to the number of dimensions for which the crystal is periodic. The prevention of propagation occurs even though the material in its solid form is transparent at these wavelengths.

Since their discovery and first demonstration in the late 1980's, interest in photonic crystals has grown explosively. Owing to the potential of PBG structures there is a plethora of applications in which they could be used. In the (sub)mm-wave range some applications have attracted a lot of attention, like e.g. imaging arrays which are of great interest for space astronomy, atmospheric research or security systems. Also in the low millimetre wave range many commercial applications are already known and can for example be found in the field of diagnostics, autonomous aircraft landing systems, car collision avoidance, traffic management, etc. The use of PBG's for these applications can have some advantages with respect to the conventional solutions. For instance, the problems related with surface wave excitation that planar antennas have, can be overcome using PBG substrates. In relation with their fabrication, systems based on PBG's may involve less processing steps while preserving system performance. It is also foreseen that using this technology it should be possible to make fully 3-dimensional circuitry allowing to build more complex systems.

In this paper some PBG (sub)mm-wave components are presented. Both radiating configurations, i.e. combinations of PBG's and dipole antennas, and waveguides have been studied. Finally as an example of the combination of PBG's and active devices, results of a PBG mixer are shown.

Woodpile structure

The PBG structure that has been used in all of the experiments is the woodpile or layer-by-layer [1,2]. It presents a full band gap of around 20% bandwidth. This structure is a good candidate to be used in this frequency range, since it is robust and the manufacturing processes involved in its fabrication using silicon are not very complicated [3]. Two different structures were fabricated, one with working frequency around 250 and another around 500 GHz.

In Figure 1, the response of the 500GHz woodpile under normal incidence is presented. There is a gap around 500 GHz with more than 30dB rejection level (5 periods have been used in the stacking direction). The identical response for both polarisations indicates that the fabrication errors are negligible.

Antenna applications

Because of its ability to suppress unwanted radiation in 3-dimensions, 3D Photonic crystals have attracted much interest in the field of antennas. Whilst 2-dimensional Photonic crystals have proven to be a useful substrate for planar antennas, a 3-dimensional Photonic Crystal seems even more desirable because any antenna fundamentally radiates in 3-dimensions.

One of the problems encountered when trying to integrate antennas with circuitry is that planar antennas on high dielectric constant substrates couple a significant fraction of the input power into substrate modes. Since these do not contribute to the primary radiation pattern, substrate mode coupling is generally considered as a loss mechanism. By removing the possible existence of substrate modes by using a PBG substrate this problem can be overcome, exemplifying the application of PBG materials.

An integrated antenna system consisting of a dipole antenna placed on top of a woodpile structure was built. Its radiation pattern at 500 GHz [4] is shown in figure 2. The back radiation has been significantly reduced thanks to the presence of the PBG. It should also be noted that the obtained E-plane beamwidth is ≅ 44º while it is ≅ 64º for the H-plane (taking into account only that half of the pattern that was not disturbed). These values correspond to an estimated effective area of $1.3\lambda_0$ in the E-plane and $0.78\lambda_0$ in the H plane. This area is much larger than that of a simple stand-alone dipole that has an effective area of $0.13\lambda_0^2$.

The radiation reduces significantly in the end-fire direction, showing that this configuration also reduces the mutual coupling between antennas. Since parasitic cross coupling has limited severely the application of planar antennas in imaging arrays, the use of PBG's presents a possibility of alleviating this problem.

PBG waveguides

In order to get the most out of PBG technology, a full PBG system should be designed, avoiding the transitions between different technologies. To achieve this objective, the individual components that constitute a RF system should be realised in PBG technology.

One of the basic components is waveguides. The main advantage of PBG over micro-machined waveguides are that there is no need to coat in metal nor therefore to make a good electrical contact. This simplifies manufacture, increases reliability and should reduce loss. Also the fabrication is considerably simpler as identical etches are used on each side of the wafer, whereas micro-machined waveguide circuitry typically requires multiple overlaying etches, each to different depths. The number of masks and processing steps are therefore reduced accordingly.

The other main advantage is that it can be foreseen that it should be possible to make fully 3-dimensional circuitry, i.e. waveguides transversing upwards, downwards, crossways, etc… This should allow more complexity to be built into the system.

Since the output of the sources available in this frequency range still uses conventional technology, i.e. metallic rectangular waveguide, a transition from this type of waveguides to PBG waveguide has been designed as well. The waveguide has been created removing one of the woodpile bars. In Figure 5 the manufactured PBG waveguide together with the transitions to metallic waveguide are shown. They were fabricated using the Deep Reactive Ion Etching, which provides the means to manufacture accurate structures that are not restricted to any particular crystal orientation. The simulation results show the good performance that can be achieved with these configurations. This type of waveguide is the starting point to design more complicated components like e.g. splitters, bends, etc

PBG mixer

As the frequency increases, a planar structure that integrates the antenna, mixer, local oscillator and all peripheral circuitry onto one single substrate becomes an attractive option. While conceptually simple, in practice it is challenging to develop and test an integrated planar antenna on a semiconductor substrate that has good radiation efficiency and can be easily integrated with the active circuit.

In the framework of ESA's StarTiger project, a mixer has been designed integrating PBG technology. The design that is presented here corresponds to a subharmonic mixer with RF frequency around 250GHz and uses a woodpile structure as substrate for a dipole antenna like the one presented previously. The LO power (around 125GHz) is fed using a metallic waveguide, therefore needing a transition to the Coplanar Stripline (CPS) where the diodes are placed (see Figure 4). A RF filter and a LPF are included in order to get the required isolation between ports and a good impedance matching of the diodes. The mixer shows a good performance and its measured noise temperature is presented in Figure 5.

Conclusions

In this paper the use of PBG technology in the design of (sub)mm-wave components is presented. Basic components like PBG dipole antennas and PBG waveguides have been studied. Also the results of the first PBG mixer have been presented. These demonstrate that PBG circuit architecture presents a viable alternative to conventional techniques. In general, results show that these components can benefit from the use of PBG technology.

References

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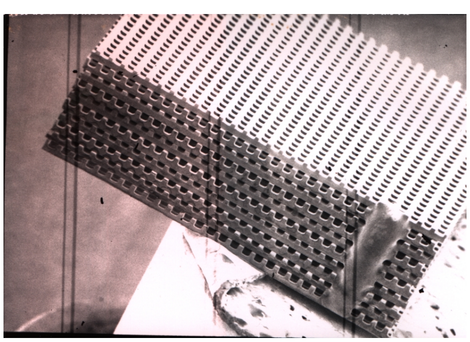
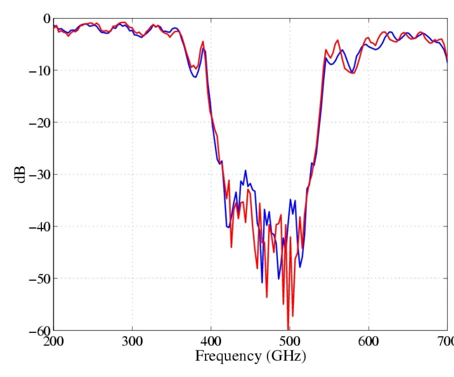
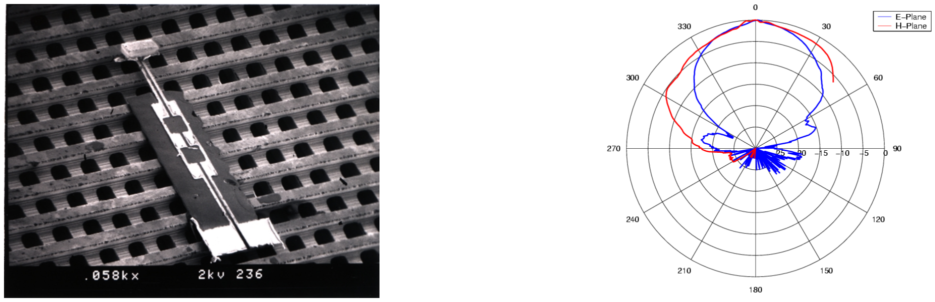


(a)



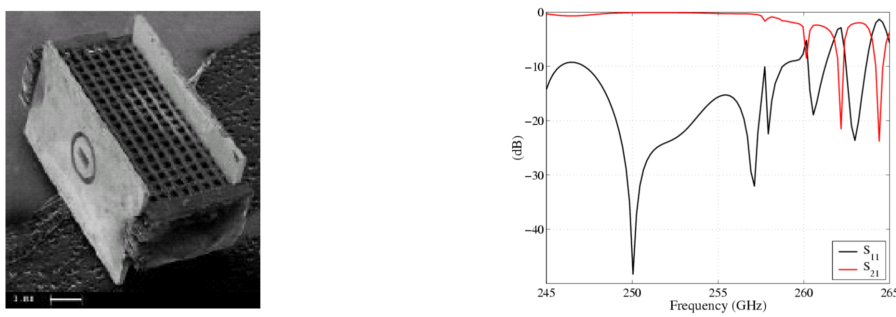
(b)

Figure 1: (a) Manufactured PBG structure (layer-by-layer). (b) Measured transmission results for parallel (red) and perpendicular (blue) polarisations.



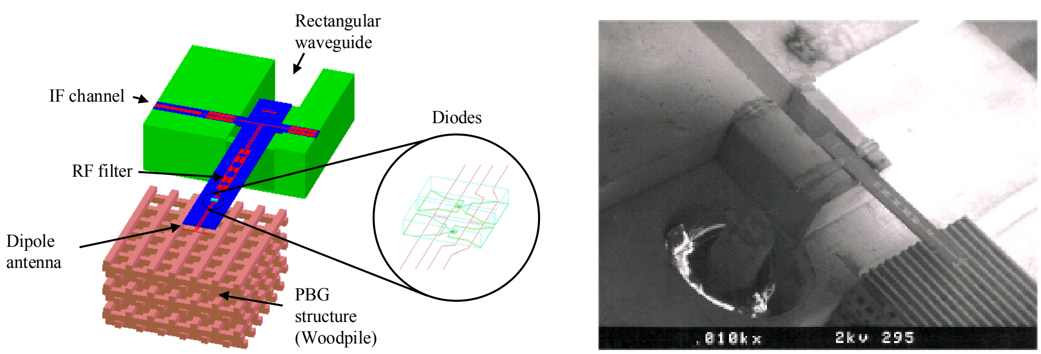
(a) (b)

Figure 2: (a) Dipole antenna on top of woodpile structure. (b) Measured radiation pattern @ 500GHz.



(a) (b)

Figure 3: (a) Back to back transition from rectangular waveguide to PBG waveguide. (b) Simulation results.



(a) (b)

Figure 4: (a) Schematic showing the PBG mixer design. (b) Photograph of the manufactured mixer.

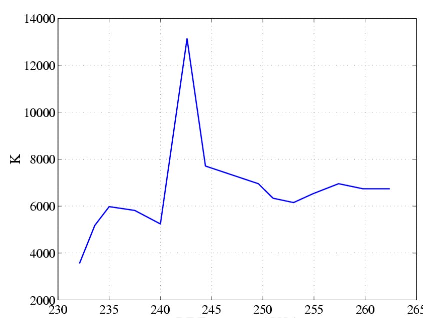


Figure 5: Measured noise temperature of the PBG mixer.