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# Dynamically-Tuneable EBG Integrated Circuits:  Final Report

## Grant No. FA2386-12-1-4062  AOARD 124062

Principal Investigators:
Prof. Michael Heimlich, Prof. Karu Esselle, A/Prof. Matekovits.

Program Manager:  Lt. Col David R. Hopper, PhD

Project Completion:  December 2013

Report Date: April 2014

## Summary

The goal of this work was to explore the properties of two-dimensional electronically-tuneable Electromagnetic BandGap (EBG) circuits, or 2DETEBGs, as frequency selective surfaces in an integrated circuit (IC) fabrication process. Previous work under an AOARD grant using printed circuit board technology for similarly constructed EBG structures successfully demonstrated the filtering characteristics of such circuits. Early design work on this project, however, demonstrated a minimal IC metallization dielectric thickness separating the two key metal layers as critical to using the previous circuit design technique, but unfortunately, commercially available IC processes are almost an order of magnitude below this value. Requests for special processing by commercial IC fabricators were unsatisfied. In light of this, a new circuit design technique was developed which showed reduced performance, but nonetheless demonstrated tuneable EBG effects. A 2DETEBG design was fabricated on a commercial GaAs process. Measured performance to date of the fabricated circuit has not demonstrated any radiating characteristics. An upgrade to our measurement system from 110 GHz to 150 GHz has been ordered as of the contract completion date, but once available we will attempt to use this enhanced measurement capability to better understand the 2DETEBG structure despite going beyond the project timeline.

The report begins with background and overview of EBG and earlier work and then leads into the design work, fabrication, and performance analysis. Sections follow which discuss project management, publications, intellectual property development, and following on-funding, and work continuing on beyond the project termination date.

Because this project ran nearly concurrently with a related AOARD project on one-dimensional EBG structures on IC (1DEBG), this report repeats some of the results from the 1DEBG final report. This is done mainly because the underlying issues limiting the 1DEBG performance and EBG behaviour in general will also limit EBG behaviour in the 2DETEBG structures studied here. While the remedy of a thicker inter-metal dielectric would bolster EBG behaviour to both 1- and 2-dimensional structures, the upgraded measurement equipment, when available in 2014, may shed separate light on each of these structure individually.

## Background – EBG concepts and Previous Work

Electromagnetic Bandgap (EBG) structures exhibit large continuous operational regions as a function of frequency over which they will not allow a signal to propagate. A subclass of bandstop filters, EBG structures "stop" a signal from passing through by having signals not propagate (vs. some other means of signal rejection, like reflection) in abeyance of Maxwell's Equations. Typically, EBG performance is achieved by modulating the geometric properties of an electromagnetic-guided or radiating structure so as to create a periodicity which induces the EBG and as such is not tuneable [1] if implemented as integrated circuits (IC) or printed circuit boards (PCB).

Previous work by this research team under Grant No. FA2386-10-1-4040 AOARD 10404 implemented a dynamically-tuneable EBG structure using printed circuit board technology at a few GHz. The periodic structure is implemented as a single, main transmission line, on top of regular series of short “patches”. The transmission line and patches are separated by a dielectric whose properties are chosen to give the desired effect EBG effect (Figure 1). In the absence of the patches, the structure would be an ideal microstrip configuration.

Tuning is accomplished by using a pair of RF/microwave switches at opposite ends of the patches (not sown in Figure 1) to isolate or connect the patch to ground, typically on the backside of the structure. With the switches open, or in the “0” state, the transmission line has a current return path dominated by the true, backside ground. With the switches closed, or in the “1” state, the current return path is dominated by a coupling from the transmission line to the patch and through the switches to ground. By choosing different combinations of switches, different periodic structures can be obtained which give rise to a variety of electromagnetic, and EBG, characteristics to move the effective ground plane of a guided structure. A detailed analysis of this can be found in [6].

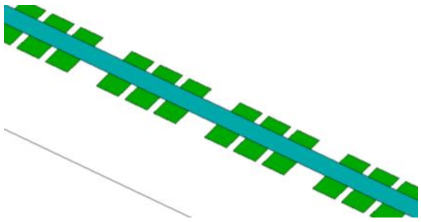

Figure 1 – Periodic two-layer EBG structure with main transmission line on top layer (blue) and patches in 4 groups of 3 on second layer (green).

The benefit of these structures are large bandwidth switching whose switching times would be on the order of switching time of the underlying device. Whereas MEMs structures would be on the order microseconds, and packaged FET switches on the order of tens of hundreds of nanoseconds, an IC process which integrated these structures could in theory switch at sub-nanosecond rates.

The aim of the previous project was to create a PCB demonstrator of the switchable EBG structure based on the prior theoretical study on IC [2, 3].

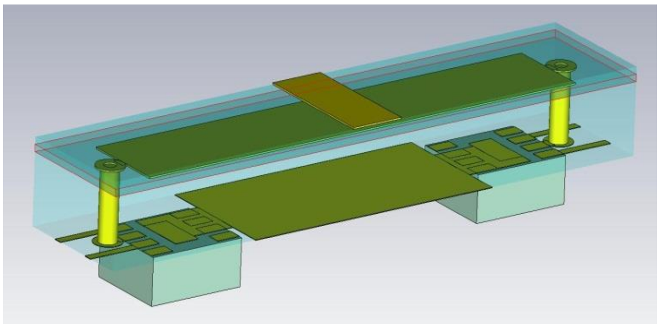

Figure 2 – Conceptual design used for PCB demonstrator: thru-vias (yellow) connect the patch to the backside switches (gray blocks) to open/close current path to ground plane (large green rectangle on lower level). Top level (green) line is the main transmission line

Because of PCB fabrication requirements, the initial structure was modified as shown in Figures 2 and 3. Instead of switches on the front, the switches were placed on the back with the normally uniform ground plane corrupted and broken up so as to support switching control lines to the edges and active signal lines from the thru-vias to the switch pads. 48 switches, or 24 patches were constructed to give a high variety of switched states, which were mainly grouped as 8 unit cells of 3 patches.

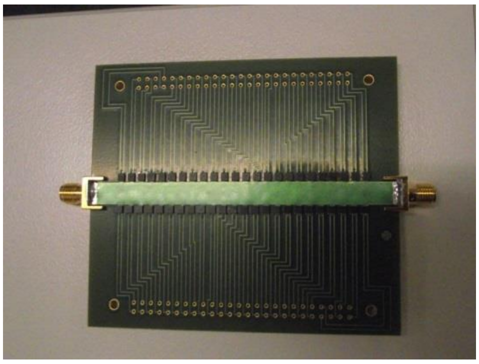

Figure 3 – Fabricated EBG Demonstrator with mounted switches

Measured data for the PCB demonstrator were encouraging (Figure 4). Extremely steep transitions from transmission to non-transmission were observed in the switched states with somewhat higher than desired insertion loss in the 0000… state. Changes in switching states could accomplish as much as a 2x change in the bandwidth of the stopband.

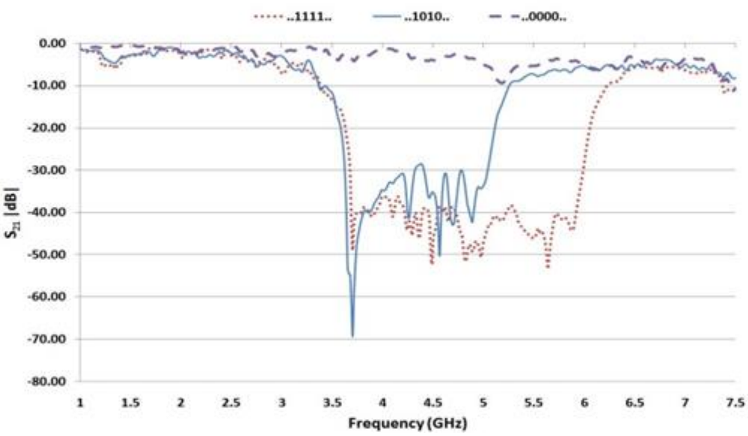


Figure 4 – EBG Demonstrator PCB with configurations "...1111…", "…1010..." and "…0000.." [3]

The aim of this current project is to return to the original concept of front-side, integrated switching, with a uniform backside ground plane, and implementation in IC technology, with the crucial, additional requirement of establishing tuneable EBG behaviour in two-dimensions.  The benefit of such and EBG structure with IC technology is to incorporate signal processing antennas and frequency selective reflectors/absorbers with the underlying electronics to control and analyse the associated signals.

**Detailed Project Objective and Initial Designs**

In this section, the objectives of the projects are reviewed from the systems perspective developed out of the PCB work.  The relation from an initial design concept perspective, between 1D and 2D is introduced with a continuing consideration of developing 1D EBG behaviour as a precursor and foundation for the 2DETEBG.

According to [2], the structure needs to have several key features (as shown in Figure 1) we are apparent from our understanding of the 1D PCB demonstrator:

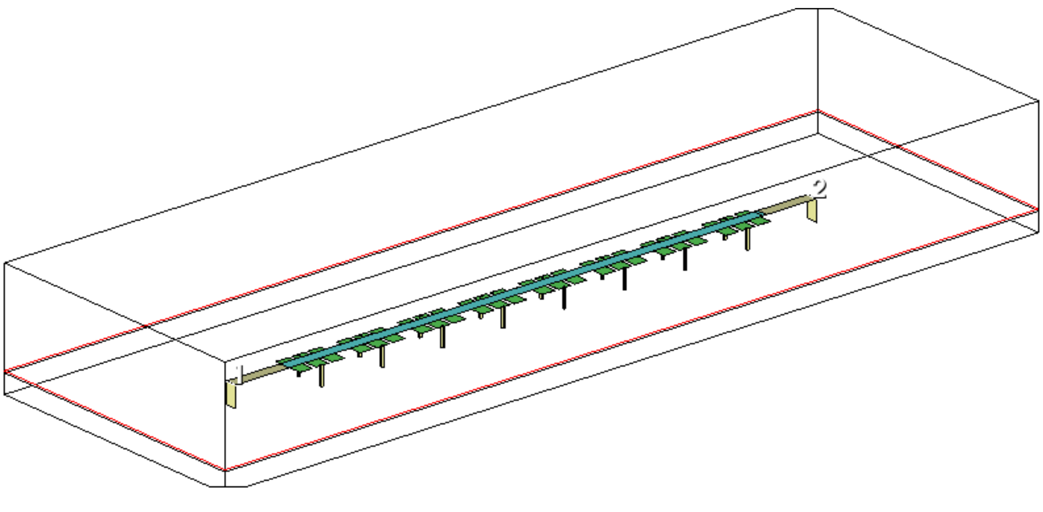


Figure 5 – Theoretical EBG structure for IC

1. A thick, low-loss dielectric substrate with a ground plane on the back. Bottom-most layer shown in box edges in Figure 1.
2. A top-layer metal conductor which, when placed on the top of item 1, implements a high-quality microstrip transmission line. Blue line in Figure 1.
3. A very thin, low-loss dielectric layer inserted between items 1 and 2. Middle (reddish) layer shown in box edges in Figure 1.
4. Periodic metal patches transverse to item 2 and on the bottom side of item 3(i.e. between the items 1 and 3). Green structures in Figure 1.
5. Conducting vias located beyond the ends of metal patches in item 4 which connect to the ground plane of item 1 through a selectable electronic switch capable of passing RF/microwave signals at some lower frequency switching rate; the switching speed is unimportant for this project. Gold vertical rectangles in Figure 1.
6. Switches connecting the vias, item 5, to the patches, item 4. Not shown in Figure 1.
7. A 2-dimensional structure capable of radiating electromagnetic energy across a surface, in this case, a planar surface defined by the IC's circuitry and metal interconnects.

Initial design considerations associated with items 1 through 6 focused on the dielectrics and their thicknesses that physically separate items 1, 2, and 3. Nominally, the "height", of a microstrip transmission line is defined by the distance between items 1 and 2. This height is referred to here as $h_1$. If item 3 is acting as a surrogate or weak ground for the main transmission line (item 1), then the separation (or height or thickness) between items 2 and 3 is also of importance. This height is referred to here as $h_2$. Thus, the EBG effect can be understood in this interpretation as a dynamic changing of the distance between item 1 and its "ground" when switched patches in a series create a periodic pattern. Large changes in this effective ground plane height give rise to large changes in the effective dielectric constant of the microstrip configuration, thereby creating the EBG effect if repeated in a regular, periodic manner [2]. This EBG effect, if it is to be part of a frequency selective surface must exhibit radiating characteristics, and in a large-aspect ratio configuration (i.e. a structure that is longer than it is wider) it is reasonable to anticipate that it should be a radiating in the one long dimension (for a 1D structure that is reduced from the related 2D structure).

Manifestly, the frequency selective surface would be expected to exhibit antenna-like characteristics across two independent variables. Holding frequency constant and varying the EBG switch pattern, we would expect to see changes in directivity such as to accomplish "beam steering" from the EBG structure. In this mode, the ability to rapidly switch the pHEMT switches in the EBG structure would allow sub-nanosecond state changes. Conversely, holding the switch state constant, the surface would act like a "classical" antenna structure and provide some spatial discrimination across frequency, where directivity would vary over some finite frequency band.

By extension from 1-dimension, in 2-dimensions, we would expect the surface as a whole to change its radiating characteristics simply because the effective dielectric constant in 1-dimension was changing, thus changing the overall 2D characteristics. Conceptually, modulating the dielectric constant in 2D is possible, but not practical as two distinct sets of switches would be needed: one for each dimension. This would offer interesting opportunities in terms of tuning the polarization, but would difficult in practice due to parasitic and detrimental interactions and couplings would occur between the two sets of switching circuits.

Returning to the 1D case, by using values of $h_1$ = 51 µm and $h_2$ = 1µm for a GaAs IC process, simulations showed promising results for a 12 patch structure that had patches 28 µm wide on 150 µm centers. The main transmission line structure was chosen to be 31 µm wide which gave a nominal 50 ohm characteristic impedance on 2 mil (50 µm GaAs). All metallization is gold. This structure, if fabricated on a theoretical GaAs IC process was simulated using AWR AXIEM 3D planar EM solver (Figure 6) to have an EBG in the 30-150GHz range depending on quality of the switches, the thru-via configuration, and the metallization among these switching-related structures.

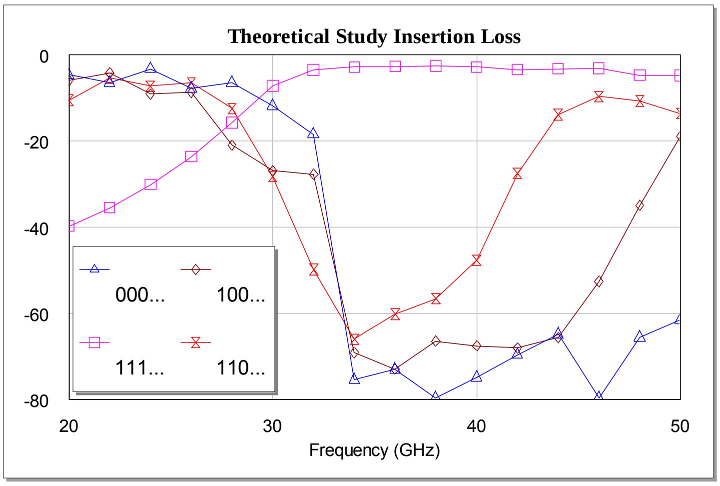


Figure 6– Theoretical study on 50um GaAs IC for 4 dynamic switching states shows expected performance per earlier PCB study.

## 1D Implementation and Redesign: EBG IC proof-of-concept

This project focuses on the 2DETEBG structure, however to get a 2D structure with EBG characteristics, the approach here was to establish a 1D EBG capability on IC and then leverage the 1D structure as a “known good starting point” to develop the 2D structure. In this section, the transition from PCB to IC 1D EBG structure is reviewed.

The basic design for a 1D structure was transitioned to WIN Semiconductor’s recently released PP10 GaAs pHEMT process on 50 um substrates. PP10 was chosen mainly because of its very high $f_t$ (160 GHz in wafer-probed PCMs and over 250 GHz for the intrinsic devices in separate unpublished work done by these researchers) would allow the focus of this study to be on metallization configurations rather than switch limitations.

Simulated results in the production PP10 process immediately revealed two shortcomings with PP10 as a candidate process. Firstly, $h_2$ is a thin 0.15µm rather than the thicker 1µm that had initially been used in the theoretical studies. This by itself had the effect of making the coupling so strong between the transmission line and patches that it was the dominant effect rather than the perturbation to the typical microstrip configuration with the ground plane on the back. Secondly, this was exacerbated by the default WIN metal 2 (transmission line structure) being deposited on top of silicon nitride. While the latter was easily mitigated by using "airbridge" to substitute relatively benign air for the higher dielectric silicon nitride, the former became the focus of an intense and in-depth redesign.

The immediate remedy to this problem was to find a commercial IC process which had a thicker interlayer dielectric among the metallization layers. WIN did not offer such an option, nor did Triquint Semiconductor (USA, GaAs vendor) or Silanna (Australia, silicon on sapphire). It was decided to continue with PP10, again because its superior bandwidth gave greater latitude in observing EBG effects.

A redesign of the structure was undertaken which essentially required minimizing the capacitive coupling between the transmission line on layer 2 and the patches on layer 1 with $h_1$ = 50µm and $h_2$=0.15µm, the nominal values for PP10.

The 1D design finally settled upon was somewhat of a departure from all the previous concepts or implementations of EBG structures by this research team. Instead of a continuous patch under the transmission line, the patch was split at the mid-way point under the transmission line and pulled back symmetrically as shown in Figure 7. In this example, the pullback is so extreme as to use purely edge coupling of the EM field lines with no physical overlap. Several different configurations for the pullback where designed and implemented. Simulations using AWR's AXIEM 3D planar EM solver are shown in Figure 8 for a variety of switching configurations. This design technique is referred to as a "split patch" rather than a full patch design.

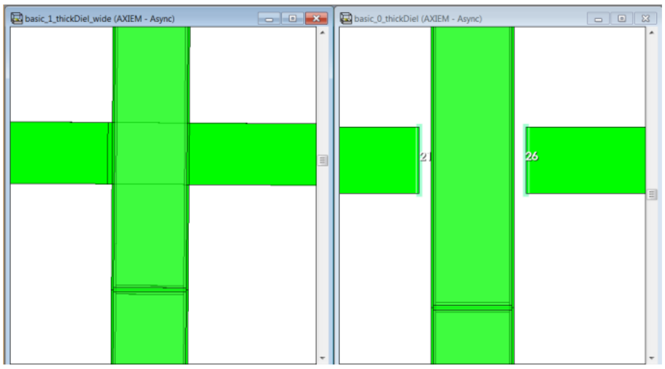


Figure 7 – Traditional (left) versus redesigned (right) IC EBG structure with the path metal (left-to-right) pulled-back from underneath the transmission line (top-to-bottom). The segmentation of the transmission line signifies use the of airspan to anchor the line in air to the substrate at distances prescribed by the PP10 process rules

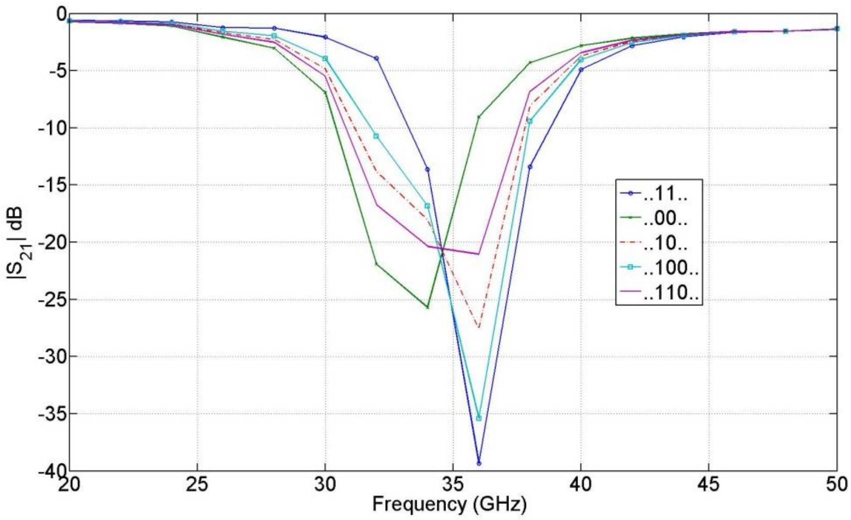


Figure 8 – Simulated results for redesigned configuration shown in Figure 6 (right). Bandwidth and roll-off at band-edge severally degraded from theoretical IC EBG structure.

The most notable feature of this 1D redesign over the full patch design with the thin dielectric is the return of some sort of controlled relationship between switching states and transmission characteristics which had been lost with the full (vs split) patch and thinner interlayer dielectric. However, the switching states no longer have as dramatic effect as with the PCB demonstrator or the IC theoretical structures presumably owing to the weaker perturbation to the ground return currents. Also note that as compared to the PCB Demonstrator, the effect of the split patch is to move the lower stopband edge rather than the upper stopband edge.

**2DETEBG Designs**

The 2DETEBG design task was done somewhat concurrently with the 1DEBG IC structures discussed in the previous section. In this first exploratory fabrication of IC EBG structures, this project and the 1D EBG IC project shared a mask. Several design considerations apart from the actual 2DETEBG performance itself entered into the design process. Foremost was that it was essential to demonstrate EBG behaviour on an IC. Transition the technology from PCB to IC inherently was the primary outcome to be accomplished in this first fabrication run, so having multiple applications (filters and antenna) and approaches (split patch and full patch) First, to keep fabrication costs to a minimum, a “4 in 1” mask was chosen then the typical “1 in 1”. This meant that the reticule size (the maximum size of the chips being designed) had to fit into approximately 9mm x 10mm. With two designs back to back in the 10mm direction, this meant that the maximum chip size would have its largest dimension as 5mm but effectively, with bond pads and room for saw street, this left just a little over 3mm for the longitudinal, or propagating, length of the EBG structure, In GaAs microstrip on 50 um thick wafers, 3mm as 1 wavelength corresponds to a frequency of about 35 GHz but with the loading of the EBG patches, this tended to make the lines look electrically shorter, thus pushing this frequency up. Second, 2D structures took up considerable room on an already small reticule, so rather than having only 1 or 2 designs of the full 2D structure that could act like complete surfaces, it was decided to focus on simply trying to get the EBG structure to radiate and in this way, fit 4 design variants on the wafer. Finally, to further minimize risk, it was decided to explore antenna structures which did not use the split-patch design developed on AOARD 114046. The thought here was that higher coupling was twofold in that a) higher coupling to the patches was desirable in a radiating structure as a "surface" would be most effective with more energy sent along the patches and b) a single-patch design in conjunction with the split-patch 1D filter structures increased the chances of seeing the yet-to-be-seen EBG behaviour on a 50um GaAs wafer. Besides using the 1D structures as candidates for radiating mm-wave energy, 2D structures were chosen to get ever increasing representations of a true 2D structure. We treat these structures in reverse order.

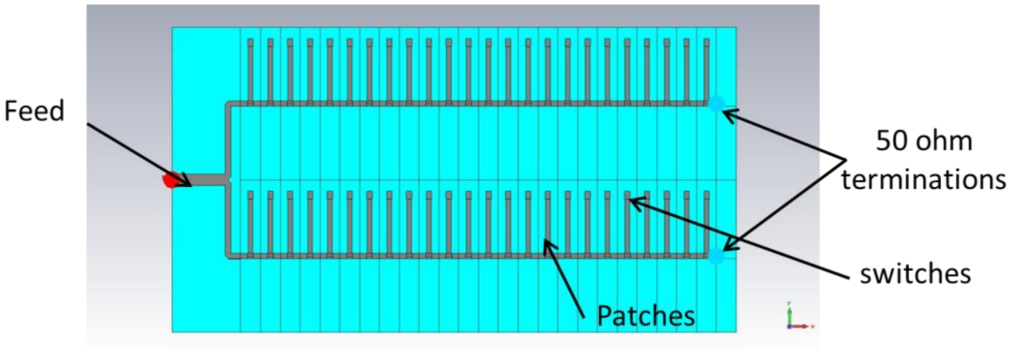


Figure 9 – asymmetric 2DETEBG antenna design (diagram form)

The first structure is a tuneable asymmetric 2D structure, shown in Figure 9 in diagram form. This structure was simulated using CST Microwave Studio, where the ON state was modelled as a short circuit rather than an electrically-correct, detailed nonlinear pHEMT circuit model. Similarly, the OFF state was modelled as an ideal open circuit separating the patch and the thru-wafer via by an area representing the physical geometry that otherwise would have been the pHEMT switch. The structure overall is comprised of two asymmetric, single EBG structures combined by a common feed. Each single structure is terminated in a 50 ohm matching load. Each EBG segment is constructed from a metal 1 patch under and perpendicular to the metal 2 microstrip line, but the patch only exists on 1 side of the line. The patch is terminated by a pHEMT switch which, when in the ON state, is grounded to the wafer backside by a thru-wafer via. A total of 24 EBG patches are used in this structure. Control lines are routed from the pHEMT to the chip's edge to provide ON-OFF control of the switch.

Simulation results for directivity as a function of frequency for a fixed switch state (111…) and directivity as a function of switch state for a fixed frequency are shown in Figures 10 and 11, respectively. This structure was studied in simulation only, but was not chosen to go in the fabrication run owing to the fact that it takes up nearly three times the size of the structures that eventually were fabricated. Also, nonidealities introduced by the switch control lines—especially those contained within the confines of the "surface" as defined by the two microstrip lines—were deemed to create an undue amount of risk in realizing in measurement the simulated performance.

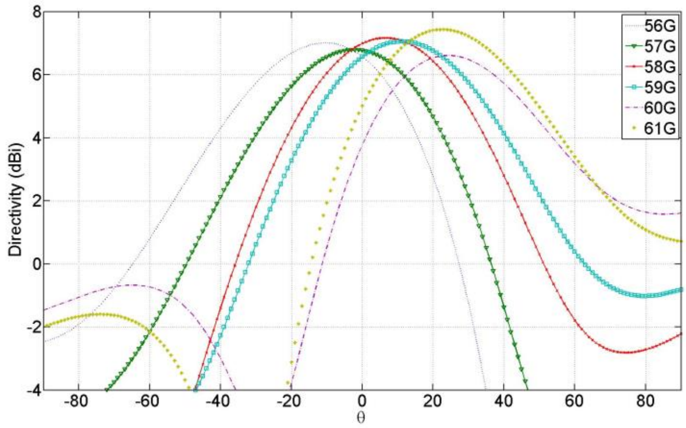


Figure 10 – Directivity (dB) for a fixed switch configuration (111…) as a function of frequency (GHz).

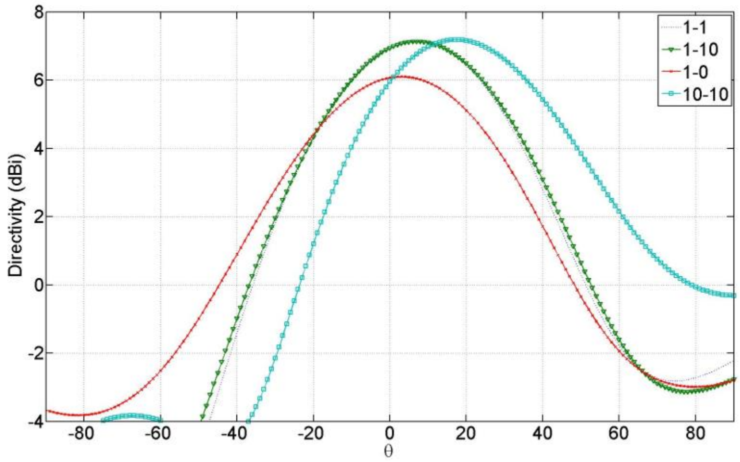


Figure 11 – Directivity (dB) for a fixed frequency (58 GHz) as a function of switch configuration.

The second structure is a 1D version of the previous structure, as shown in Figure 12. The feed is simplified to a direct connection to the launch pads as there is no need for a symmetric manifold to a second microstrip line. The line is still terminated in 50 ohm load and the EBG patches on metal 1 are single-sided with respect to the microstrip line on metal 2.

Simulation results from CST Microwave Studio are shown in Figures 13 and 14, where the pHEMT switches were substituted for ideal shorts (state=ON) or ideal opens (state=OFF), as was done with the 2DETEBG structure, above. The directivity at a fixed switch state (111,,,) over frequency appears to be more regular and monotonic with frequency than that for the 2D structures, suggesting that the two “arms” of the 2D structure are creating an irregular phase shift that adds, similar to how a phased-array works, but here the spacing and phase control which has not been optimized to scan smoothly over frequency. This, of course, is not an issue with the 1D structure. Similarly for the fixed-frequency, variable tuning simulations, the 1D structure appears to have a much more pronounced impact from the EBG tuning than in the 2D case.

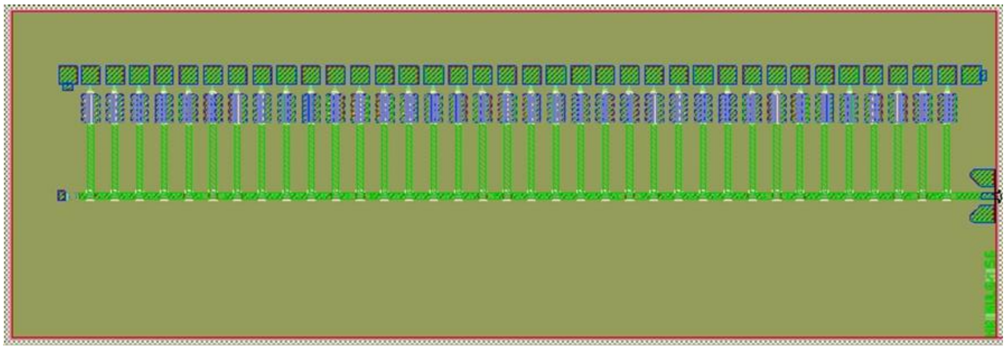

Figure 12 – asymmetric 1DETEBG antenna layout

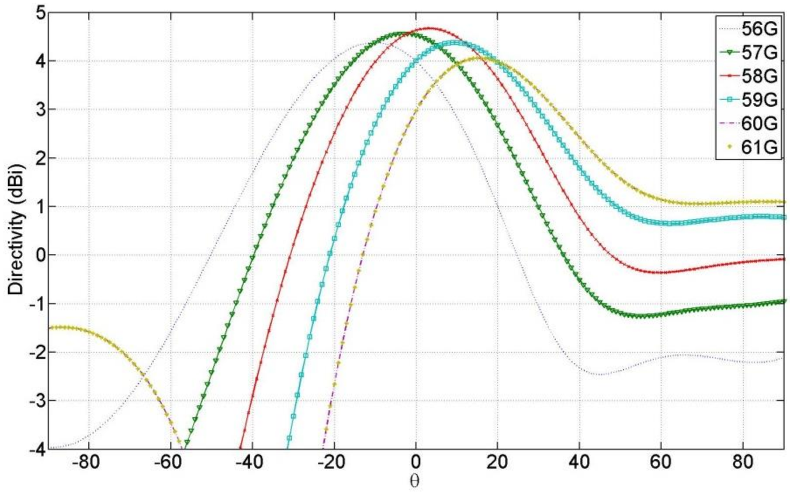


Figure 13 – Directivity (dB) at a fixed switch state (111…) as a function of frequency (GHz)

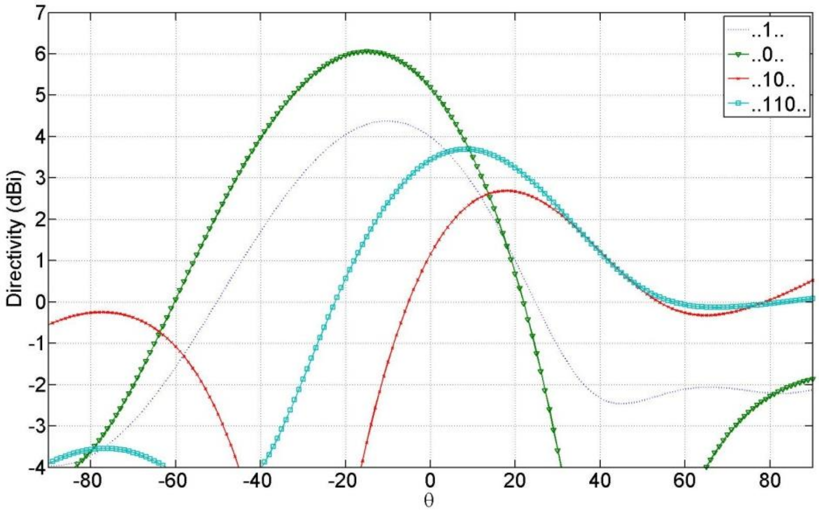


Figure 14 – Directivity (dB) for a fixed frequency (56 GHz) as a function of switch state

Finally, a fixed 1D asymmetric structure was designed (Figure 15) and laid out for fabrication. The structure is comprised of 12 alternating pairs of patches, one grounded and one open, emulating switches in this configuration for a total of 24 EBG segments. This structure was included in the fabrication as it represented most closely what had been simulated in CST, and it was felt that this would give the best chance of observing EBG behaviour, albeit in a fixed and non-tuneable form.

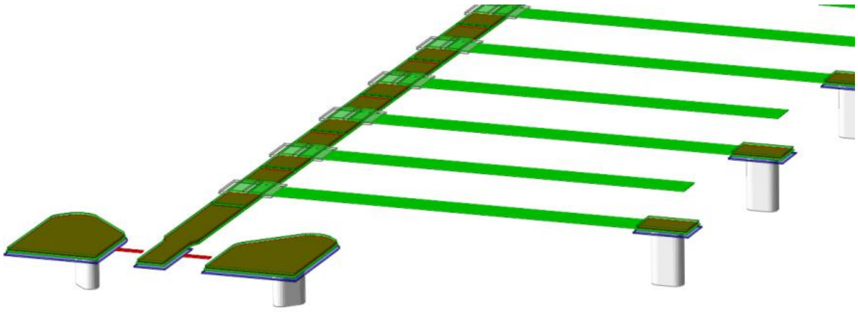

Figure 15 – Idealized 1D EBG “surface” circuit representing in layout what was simulated in CST for the 1D structure shown in Figure 12.

The designs were fabricated at WIN Semiconductor’s Taiwan GaAs foundry in the production PP10 process with a wafer thickness of 50um. Co-located on the wafer were the designs for the EBG filter circuits from AOARD project 114046 along with the two 1D asymmetric designs mentioned above. There was insufficient room in this initial fabrication run for the 2D circuit. The simulation results for the 2D design did not demonstrate superior performance over the 1D asymmetric design to a degree which encouraged its inclusion. Wafer-probable samples were delivered with an option for post-test dicing that will be exercised to make available die for mounting in connector-based assembly (versus wafer probing).

**Measurement Procedure**

S-parameter measurements were taken with an Anritsu MS4640A 70GHz vector network analyzer at the wafer level using probes from GGB Industries. SOLT calibration was done using the on-wafer calibration structures provided by WIN Semiconductor.

**Results and Analysis**

The fabricated structures were tested with a horn antenna positioned over the die to test for any radiated power. All tested structures were found to have no measureable radiation up to the limit of the vector network analyser.

As the radiating structures were predicated on transferring the EBG behaviour from PCB to IC, the focus of the investigation shifted. Rather than trying to ascertain why there was no radiation, we felt that it was first necessary to first establish the root cause for the loss of the EBG behaviour. Thus, rather than performing analysis on the antenna structures, the analysis in what follows is based on the filter circuits. More information can be found in the AOARD 114046 final report

Simulated results (using AWR's AXIEM 3D planar EM solver) for a representative filter circuit are shown in Figure 16 and measured results are shown in Figure 17.

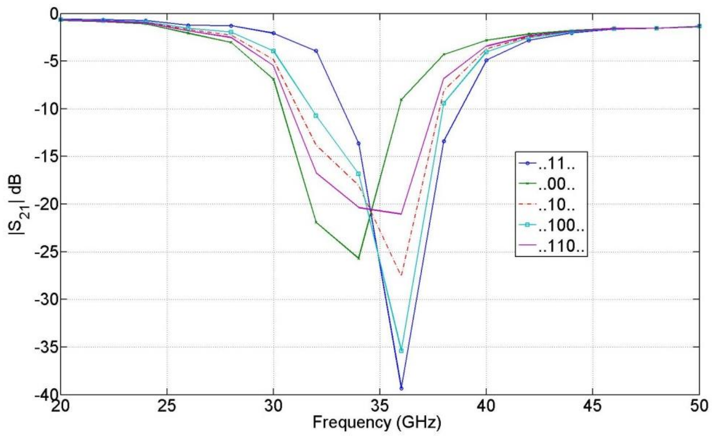


Figure 16 – Simulated transmitted signal (dB) for the representative filter design as a function of frequency (GHz) and for several switch configurations. (repeated from Figure 8)

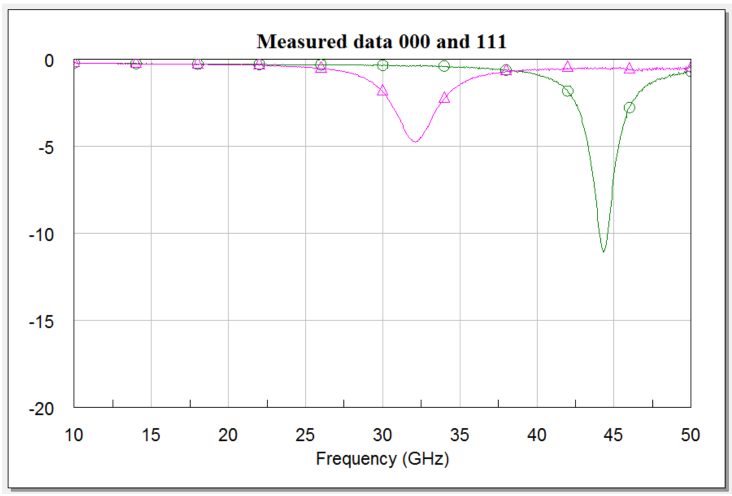


Figure 17 – Measured transmitted signal (dB) for the representative filter as a function of frequency (GHz) in the 000... and 111… states.

Two key features of these results are evident as compared to the simulated results. Firstly, one of the stopband edges is not approximately constant. In the simulated and measured (PCB demonstrator) data one of the consistent features of EBG behaviour for this class of structures is the nearly constant lower stopband edge; in the simulated split-patch design the upper band stopband edge is approximately constant. Secondly, there is a resonance in the 000… state data which has not been seen previously in simulation or measurement. When viewed together with the stopband edge phenomena, it appears that this is not an EBG circuit any longer, but instead is a resonant circuit in which the transmission line is coupling and the degree and nature of that coupling shifts the transmission characteristics. This is much more similar to changing the capacitive loading of a circuit, for example, then it is to an EBG effect.

Analysis of this data proceeded by returning to various simulation techniques with the precise layout configurations used, including the pHEMT itself which was initially ignored. Among the EM analyzers used were CST's Microwave Studio FDTD method and our own in-house CELANE solver. Results for the CELANE solver, comparing these measured data to other states—in the off chance that there was a wiring error in hard-wired state designs—is shown in Figure 18. These data to a large degree confirm the AXIEM simulations but do show among the "simulated configurations" the 000…. state having a resonance.

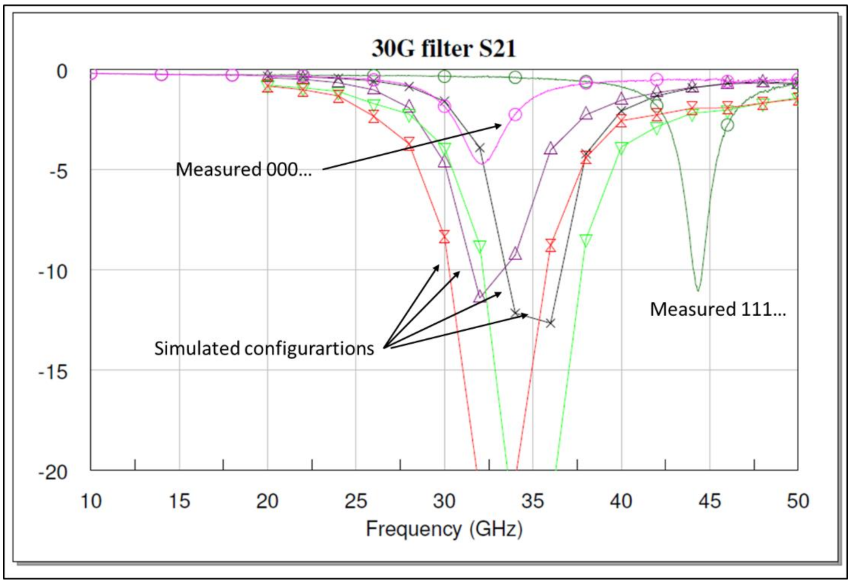


Figure 18 – Measured data (000… and 111… configurations) for CELANE solver data for several configurations, including 000….

The source and nature of this resonance have been the focus of an on-going investigation. Original effort focused on the control lines, but this has not provided any conclusive evidence and the investigation has shifted into two avenues being pursued. In the first, we are investigating the impact of the pHEMT parasitic effects which may not have been incorporated into the AWR or CST simulations. For example, the CST simulations used ideal shorts/opens in place of a pHEMT and the AWR pHEMT modelling encapsulated the pHEMT metal rather than making it part of the AXIEM simulations. In both cases, on-state series resistance and off-state capacitances where not fully part of the EM simulations. Simulations across multiple solvers with simplified structures representing this possibility will be continued beyond the termination of this project.

The second area of investigation is looking at whether EBG behaviour is at all present in this series of design. Clearly the signature marks of EBG propagation (or lack thereof) have not been seen here. However, it is possible that at higher frequency the tell-tale shift to non-propagating values for the propagation constant will be seen and transmission will cease for some finite bandwidth only to be followed by a secondary propagation mode at even higher frequencies. This effort is underway but requires improvements in our calibration technique and an upgrade to our VNA measurement capability to 145 GHz which is expected in H2 2014.

**Project Management**

This project was awarded in Q2 2012 with funding put in place in Q3 2012. At that time, the PhD student on the PCB Demonstrator project was finishing his thesis and was not available to immediately join this project. Since the time to train a post-doctoral investigator was thought to be in excess of simply waiting for the original PhD student to finish, progress was slow for the first quarter, until the thesis was completed. Because the researcher support was part time on both this project and 124062 “2D Electronically Tuneable EBG Integrated Circuits”, the same researcher was brought on to this project. The benefit of this approach was that the researcher was already well-acquainted with the subject area, challenges, and methodologies, however it did push out progress by a quarter.

After one of us (Heimlich) visited Wright Patterson Air Force Base (WPAFB) in January 2012 it was also hoped that instead of a commercial GaAs foundry, WPAFB’s semiconductor fabrication facility could be used. WPAFB. Collaborators at WPAFB pursued this but for a variety of reasons it was deemed unavailable to this project by early in H2 2012.

Using the newly released PP10 GaAs pHEMT process from WIN Semiconductor, design began in August 2012. PP10 was selected mainly because of its very high frequency performance which has the potential for lower switching speeds at mm-wave frequencies. We had already completed our first design/measurement cycle on this process on a separate project and had seen good mm-wave performance and in agreement with simulation.

The issue with the redesign has been discussed extensively in the previous technical sections. While disappointing that the PCB Demonstrator performance was not to be “cut-and-paste” on to an IC, it was rewarding in its own right because of the challenge of getting EBG performance in a more demanding form factor.

Redesign with the split-patch technique occurred in October with designs in several configurations of microwave and mm-wave frequencies and unit cell patterns completed. Layout was finished in November and manufacturing readiness (DRC/LVS and reticule generation) was completed in early December. Tape-out to WIN’s Taiwan manufacturing facility occurred in mid-December. Circuits completed fabrication in February 2013 and were received in early March 2013.

During the fabrication of the circuits at WIN, the post-doc working on the project took a full-time position at a company near Macquarie University and was being retained part-time on the project to complete the testing of the PP10 circuits, but this fell through about half-way through the testing mainly due to the testing difficulties. A 6 month extension to the project was lodged in June 2013 due to this and the other, previous delays to the progress.

Testing took place in April-June and was made difficult by the calibration with extra DC probes in place as well as because of the unexpected nature of the results. One of us (Matekovits) oversaw testing until a new post-doc was secured for the project in July-August 2013.

Pending the results of testing the first iteration designs, we planned a second run to improve the performance. This redesign and fabrication would have been done in time for a short period of testing before the new official December 2013 close to the project. The unexpected measurement results from the first-pass circuits have led to an extensive period of post-measurement analysis which has yet to yield conclusive results, but which has precluded releasing a second set of designs.

Work will continue on this project at least for the near-term based on our ability to leverage our progress accomplished under this funding for an Australian Research Council (ARC) Discovery Project grant which will run from 2013-2016. Furthermore, a post-doc familiar with these structures and how to test them will be rejoining Macquarie University later in 2014 after completing a fixed-term position at Australia's CSIRO.

**Project Outcomes**

As we have yet to ascertain a root cause for the departure among simulated and measured data for the split-batch EBG IC design(s) we have not been in a position to publish our results. However, there have been several related outcomes which would not have occurred without AOARD funding of this project.

First, an innovation disclosure has been prepared internal to Macquarie University for the split-patch design technique. This is the first step in our patent application process. Should this pass review of this initial process, the split-patch design technique and related circuits would be submitted to the formal international patent process. Should this progress beyond an internal review, AOARD will be informed

Second, while the PhD student from the PCB Demonstrator project did not see this project through to completion, the weight of activity in this area allowed us to attract a second PhD student who used our AOARD-funded work as a springboard to his research. While no funding from any AOARD project has been used in his research and he has not directly contributed to this project, his research outputs would not be such as they are without the

AOARD projects. Publications by this PhD student with the AOARD team as co-authors are given in the reference section as references 7-9.

Finally, the critical mass of research in this area at Macquarie University and Politecnico di Turino enabled us to successfully apply for an (Australian Research Council) ARC Discovery Project in 2012 with funding commencing in 2013. This is a 3-year project with $AUS 450K funding from the ARC plus additional internal University support. The EBG work done here will be extended under this project to leaky-wave structures and beam steering techniques leveraging what has been learned under the AOARD series of projects from 2010 to 2013.

## Conclusion

Leveraging the EBG PCB Demonstrator filter circuit, and its transplantation to IC technology, into 2D frequency-selective surfaces (antennas) was attempted. Lack of an available semiconductor fabrication process with the desired characteristics led to an innovate redesign of the underlying EBG subcircuit essential to establishing the necessary foundational behaviour that was to be leveraged into steerable, beam-forming, structures. A variety of configurations were simulated with a subset of these fabricated and tested in WIN Semiconductor's PP10 mm-wave process. No propagation was found which we attribute to the lack of a measureable EBG effect. The root cause of this is a point of continuing investigation beyond the termination of the project.

Several project management challenges arouse during the course of this project. The project was delayed in starting due to availability of appropriate personnel and then once they were on the project, left at a critical time in the project execution. Similarly, availability of a semiconductor process with thicker inter-metal dielectric would have simplified progress; progress was made nonetheless in transitioning a PCB design onto IC for potential high integration functionality. An extension of 6 months was applied for and granted in light of this.

While these setbacks limited the proposed outcomes, several key outcomes have been enabled by project funding. A new, innovative EBG circuit design technique has been developed. Follow-on funding for 3 years by the Australian Research Council has been enabled by this project and will allow us to pursue some of the analysis suggested here but which will extend beyond this project's completion date.

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