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Foundations of Broadband Multifunctional Metamaterials Inspired by the Analogy of Formation

ABSTRACT

The limitations of homogeneous uniform Electromagnetic Bandgap (EBG) structures are well known. For broad operating bandwidths thicker EBGs are required. For VHF and UHF frequency bands total EBG plus antenna thickness could be prohibitively large. This report presents a unique concept to design and develop broadband EBG structures. Based on the analogy of microwave filter theory a new class of Non-Uniform Aperiodic (NUA) EBG structure is proposed. Under the proposed scheme the dimensions of the patches and their inter-element distances are varied according to a taper. It is shown that a broadband (more than an octave bandwidth) directional dipole antenna can be developed with total EBG plus antenna thickness of 1/30th of the free-space wavelength. Experimental validation of the proposed concept is also presented.

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ARO STIR Project - Foundations of Broadband Multifunctional Metamaterials Inspired by the Analogy of Formation

Dr. Mohammad Ali, Principal Investigator; Email: alimo@cec.sc.edu

Submitted to: Dr. James Harvey, Program Manager, Electromagnetics and RF Circuit Integration, Army Research Office; Email: james.f.harvey.civ@mail.mil

1. Introduction

Metamaterials are artificial structures made from specific arrangements of unit cells of conductive, dielectric, and composite materials that can either enhance or inhibit electromagnetic waves. Their applications abound e.g. low profile antennas, filters, focusing, cloaking, and cross-talk mitigation in between closely spaced traces on a circuit board [1]-[31]. Simply because of the size, geometry, and material limitations of their constituent elements they have been found to be frequency dependent and narrowband. For example, consider the two structures shown in Fig. 1.

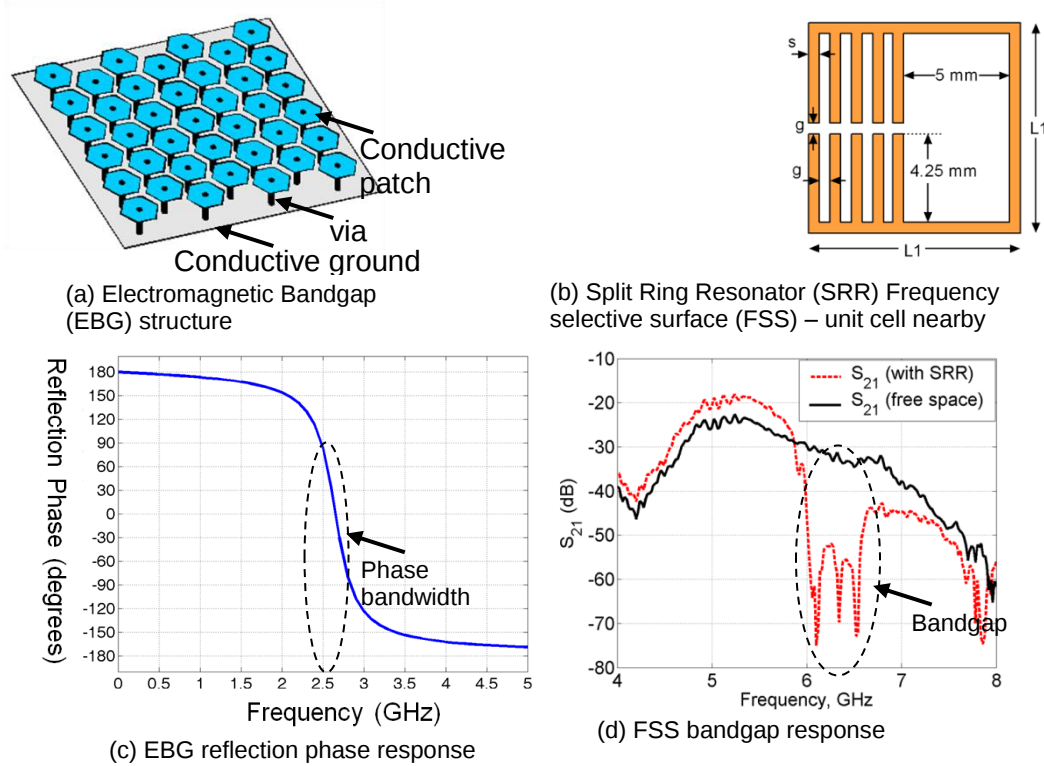


Figure 1. Traditional metamaterial examples and their limitations.

The EBG structure shown in Fig. 1(a) consists of a periodic array of conductive metal patches printed on a dielectric substrate (substrate not shown). The metal patches are shorted to the ground using conductive vias. The reflection phase, θ of the EBG varies continuously from 180° to -180° . The reflection phase bandwidth of the EBG is identified in Fig. 1(c). Similarly an FSS structure is also shown whose narrow stopband bandwidth is marked in Fig. 1(d).

It has been observed and reported by many researchers that if a dipole type antenna lies slightly above the EBG surface it will operate efficiently even though the combined antenna plus

EBG thickness is much smaller than $0.25\lambda_0$ where λ_0 is the free-space wavelength [15], [19], [21], [23]. As a matter of fact, we have reported about an antenna with combined thickness of $\lambda_0/30$ [19]. This is not possible without the EBG. In the case with no EBG the antenna must be placed at a significant fraction of the wavelength from the conducting ground below. This is a huge problem for a whole host of military applications in the VHF and UHF frequency range because of the longer wavelengths.

However, it is well known that the bandwidths of EBG based antennas have been the primary limiting factor. This occurs because the EBG structure has been nothing but a repetition of a certain unit cell in space. Wider bandwidths can be obtained but at the expense of larger thickness [16]. Similarly, tunable EBGs have been reported that utilize varactor diodes etc. which requires complicated biasing circuits and traces. Moreover, such devices are inherently power limited and at higher powers emit higher order harmonics. Needless to say that since 80% of the Army's wireless communication occurs at VHF and UHF frequencies (hence longer wavelengths), developing efficient very low profile antennas with broad operating bandwidths is crucial for future battlespace dominance.

The objective of this STIR project was to take a new holistic look at the subject of broadband EBG metamaterials from a fundamental analysis and design point of view. In order to make meaningful progress we carefully examined and addressed the following questions (1) should the EBG patches be of the same size? (2) the periodicity be the same, (3) the via diameters and the height be the same, (4) the inter-element spacing be the same, and (5) the material be the same all across?

2. Investigation Methods and Experimental Design

The focus of this short term project was to conduct a targeted investigation on EBG metamaterials in the UHF frequency band on the prospects of achieving broad bandwidth. The research involved extensive electromagnetic modeling and simulations using Ansys HFSS. A fat wideband dipole antenna was used as the illuminating source to understand the behavior of the EBG structure below. The VSWR and radiation properties of the antenna were studied in the presence of many different EBG structures. Finally, an experimental prototype antenna plus EBG was built and tested that validated the findings from the simulations.

3. Results

3.1 The Fat Dipole Antenna in Free-Space

As opposed to plane wave illumination and reflection phase simulations we focused on illuminating the EBG surface using a fat dipole because that is a more realistic scenario. Moreover, this allowed us to investigate a whole host of EBG structures which are not made from a repetition of the same unit cell. Note that computing the reflection phase of a uniform EBG is fairly straightforward because one can use only one unit cell and then apply the periodic boundary conditions. This is not possible for EBGs with non-uniform patch sizes and distances.

A fat dipole was chosen because of its broad bandwidth. The dipole was made of two conducting strips each measuring 160 mm (length) by 110 mm (width). The two metal strips were separated by a 10 mm gap and was excited using a gap excitation in HFSS. The impedance vs. frequency and the VSWR vs. frequency of the source dipole are shown in Fig. 2. As apparent,

the antenna operates from 300-900 MHz within VSWR=3. The pattern and gain bandwidths extend from 330-900 MHz.

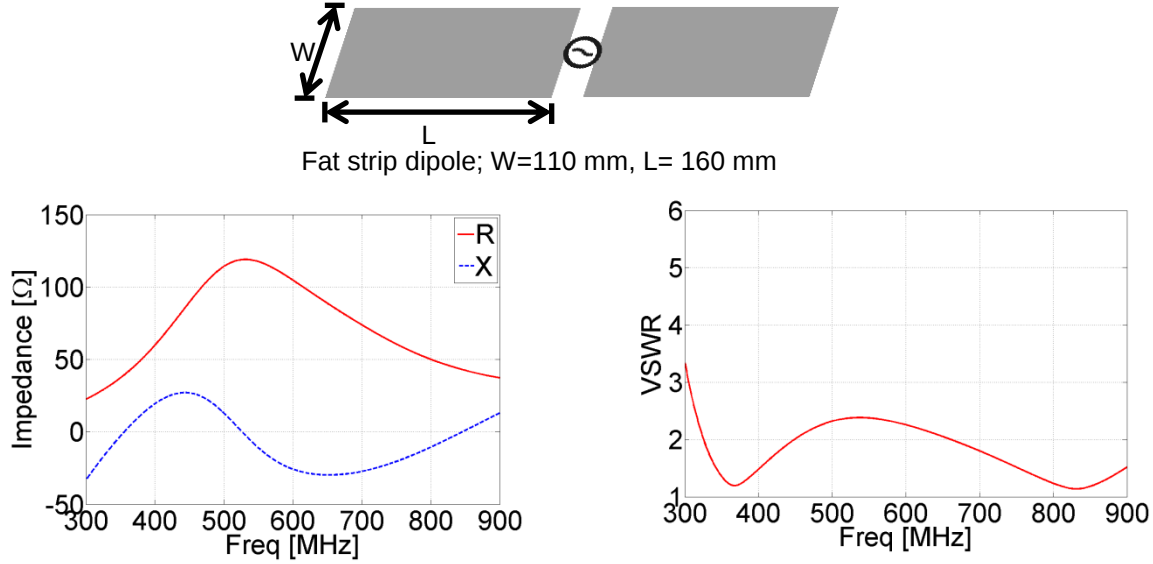


Figure 2. Simulated impedance and VSWR of a fat strip dipole in the UHF band.

3.2 UHF Wideband Dipole on Uniform EBG Surface

Following our previous work on wideband EBG design in the 1750-2500 MHz frequency band [23] the unit cell size of a baseline uniform UHF EBG was determined. The strip dipole described above was then placed 1 mm above a uniform UHF mushroom EBG surface consisting of 8 by 8 patches each measuring 50 mm by 50 mm. The separation distance between the patches was 5 mm. The total length of the EBG surface was 435 mm. Each EBG patch had a 2 mm conducting post connecting it to the ground below (see Fig. 3). The total EBG thickness was 25 mm and both $\epsilon_{r1}=\epsilon_{r2}=4.5$ (FR4).

As apparent from Fig. 3(b) the fat dipole antenna on the EBG operates from 430 MHz to 620 MHz giving a frequency ratio of 1.4 or 40% bandwidth. Antenna radiation patterns (both principal planes) computed at 500 MHz are shown in Fig. 3. Patterns are directional with peak gain of 6 dBi and front to back ratio (F/B) of about 18 dB. Three dimensional realized gain patterns at 440 and 550 MHz are shown in Fig. 4. It is clear that the patterns are directional and well defined. Peak realized gain data for the same antenna on the uniform EBG are listed in table 1. Peak gain varies from 1.9 to 5.99 dBi.

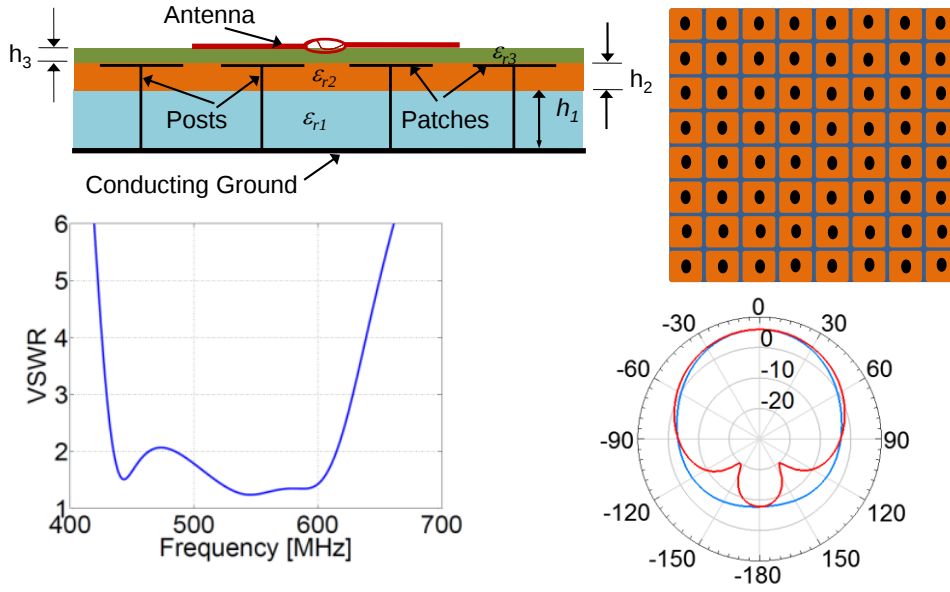


Figure 3. A fat strip dipole on a uniform EBG surface; VSWR vs. frequency and normalized radiation pattern (500 MHz).

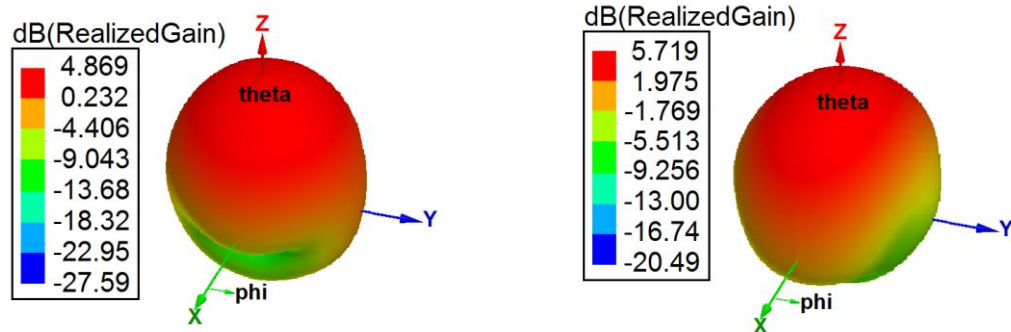


Figure 4. Three dimensional radiation patterns at 440 and 550 MHz.

Table 1: Realized gain data as function of frequency. UHF EBG and UHF wideband dipole.

Frequency (MHz)	440	500	550	575	585	600	620
Realized Gain (dBi)	4.87	5.99	5.72	4.41	3.66	2.25	1.93
Directivity (dBi)	5.78	7.02	6.37	5.2	4.56	3.46	2.55

The same antenna on an EBG consisting of 10 mm thick FR4 and 15 mm thick foam showed about a 50 MHz of frequency shift towards the right (Fig. 5). This clearly shows that a combination of dielectric material plus foam of proper thickness can be used to allow the development of a low cost light weight system.

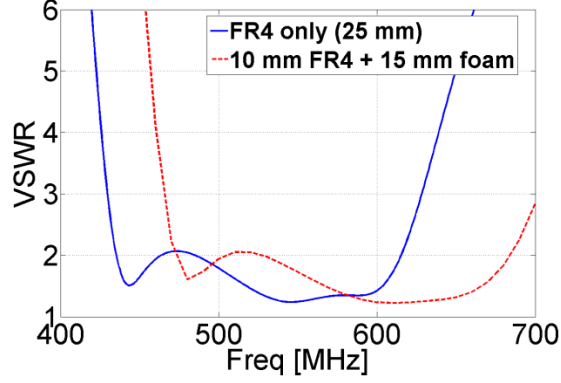


Figure 5. Simulated VSWR vs. frequency of wideband UHF dipole on EBG on FR4 only and FR4 plus foam substrate.

3.3 A New Approach to Design and Develop Broadband EBG Metamaterials

A. The Tapered Broadband EBG Concept

Following the analogy of microwave filter theory research investigations were carried out with non-uniform EBG structures. Since no known methodology to allow any specific mathematical or tapering profile exists for EBG structures we considered the same EBG volume as before and investigated as the geometry was adjusted according to a percentage of taper. Thus the total surface area of the EBG was 435 mm by 435 mm and the thickness was 25 mm. The material under consideration was also FR4.

Both an increasing and decreasing taper were considered. The mathematical method of tapering and the taper variables are described below

$$a_{i+1} = r a_i \quad (1)$$

$$s_{i+1} = r s_i \quad (2) \quad \text{where, } i = 1, 2, \dots, (n/2 - 1) \text{ and}$$

$$r = \left(1 \pm \frac{p}{100}\right) \quad (3) \quad \text{for } p \text{ percent increase or decrease}$$

Note that the variable a_i is found as follows:

$$a_1 = \frac{\frac{n}{2} a_{base} (r - 1)}{r^{\frac{n}{2}} - 1} \quad (4)$$

The variable s_l is found by keeping the total length L constant

$$s_1 = \frac{L(r-1) - 2a_1 \left(r^{\frac{n}{2}} - 1 \right)}{2 \left(r^{\frac{n}{2}} - 1 \right) - (r-1)} \quad (6)$$

For example, for $n = 8$, $L = 435$ mm, $a_{base} = 50$ mm, $p = -20$ (for 20% decrease) the parameter values listed in Table 2 result. The corresponding geometry is shown in Fig. 6.

Table 2: A 20% decreasing taper; patch dimensions and inter-element spacing (mm).

a_1	a_2	a_3	a_4	s_1	s_2	s_3	s_4
68	54.4	43.5	34.8	6.8	5.4	4.4	3.5

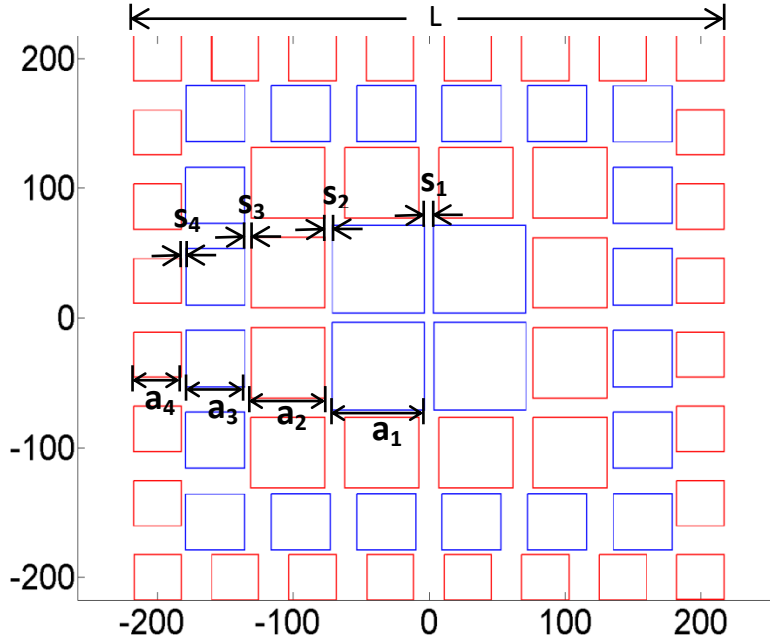


Figure 6. An EBG with 20% decreasing taper.

B. Results of Increasing Taper

The initial hypothesis was that the center elements of the EBG should be smaller and the distant elements should gradually grow larger in size. This argument has its support from our knowledge of traveling wave antennas. For example, consider a broadband spiral antenna. The actual physical location of its active region shifts as the frequency changes. The region near the feed is responsible for the high frequency radiation while the distant region is responsible for the low frequency radiation.

With this hypothesis in mind various tapering schemes were considered. The geometrical dimensions of the EBG were determined using (1)-(6). The same fat strip dipole was placed 1 mm above each EBG structure. Also the thickness of the EBG was 25 mm fixed and the dielectric material was FR4. Each EBG patch had a 2 mm diameter metal post shorting it to the ground below.

The simulation results of an increasing taper are shown in Fig. 7. Each chart represents the VSWR vs. frequency characteristics of the same fat strip dipole on an EBG with the specified taper. The larger the percentage of the taper the larger is the variation between the patch sizes and the spacings between the patches. As the taper increases from 2% to 5% the VSWR response worsens progressively. Further increase in taper resulted in even worse performance. These results are corroborated by the impedance Smith chart plots of Fig. 8. Clearly increasing the taper made the impedance match of the dipole progressively worse.

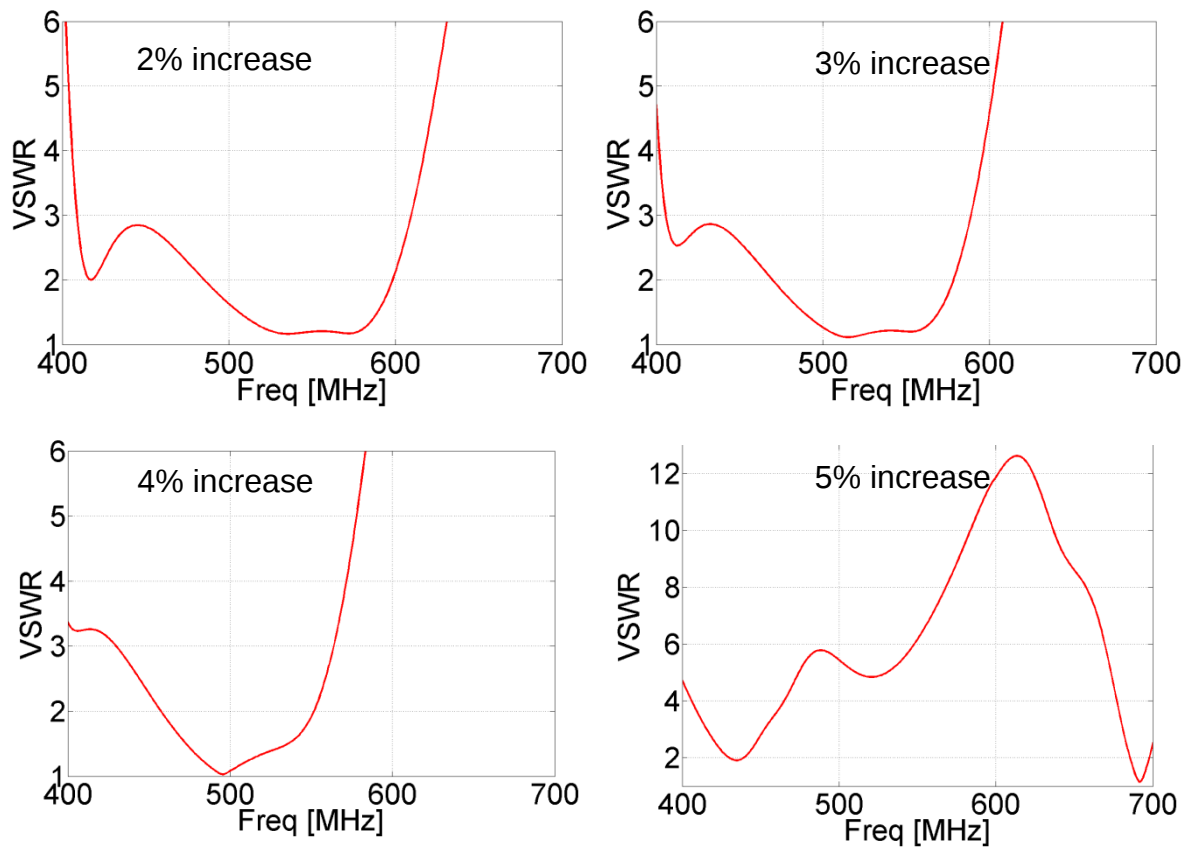


Figure 7. Simulated VSWR vs. frequency of tapered EBG (increasing taper) and fat strip dipole.

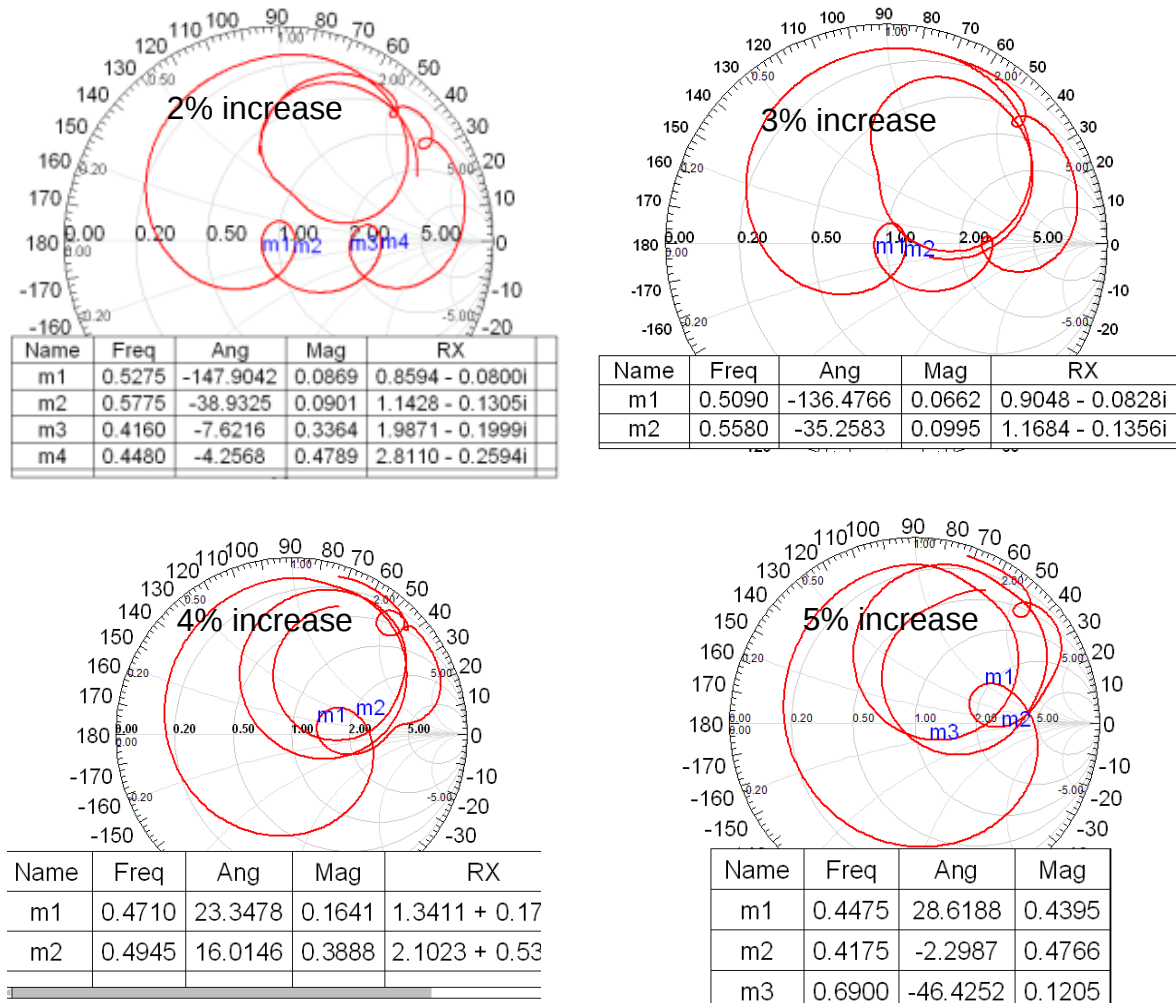


Figure 8. Simulated impedance vs. frequency of tapered EBG (increasing taper) and fat strip dipole.

C. Results of Decreasing Taper

The next logical step was to consider the reverse case where the center EBG patches are the largest. Naturally the inter-element spacings are also the largest for the center elements. As one moves outward from the center the patch sizes decrease and their inter-element spacings also decrease as given by (1)-(6). The rationale behind this hypothesis lies in the fact that the illuminating source, the dipole above has its peak current at the center. And the current falls off as a sinusoidal function along its length.

For example, the case of a 20% decreasing taper is shown in Fig. 6 and the geometrical dimensions are listed in Table 2.

Again as before the total length and width of the EBG surface was fixed. The EBG thickness was 25 mm and the substrate was FR4 as before. Each patch was shorted to the conducting ground below with a 2 mm diameter conducting post. The same fat strip dipole was placed 1 mm above each EBG surface as the illuminating source.

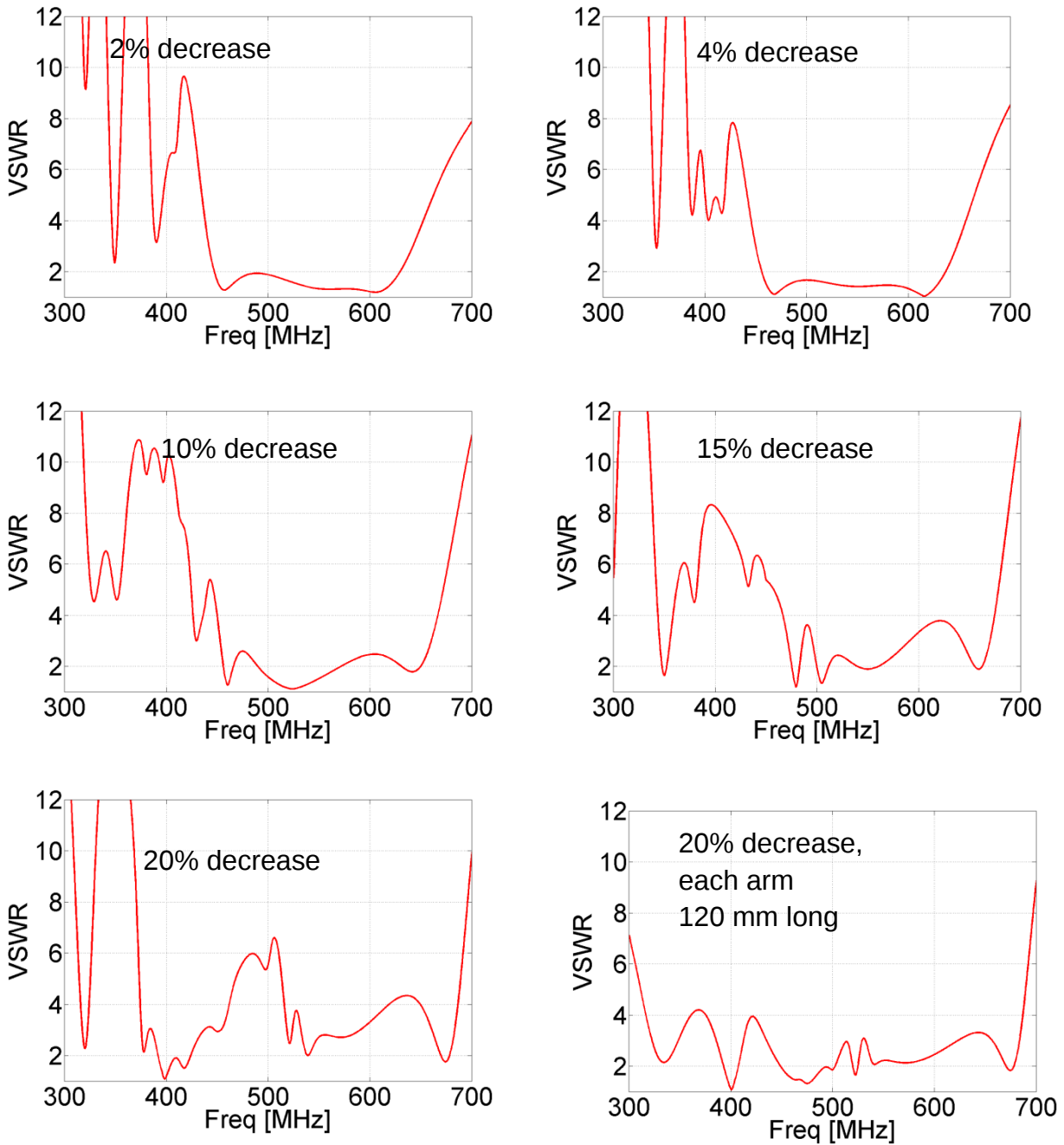


Figure 9. Simulated VSWR vs. frequency of tapered EBG (decreasing taper) and fat strip dipole.

Fig. 9 shows the simulated VSWR vs. frequency characteristics for a number of cases. Clearly as the amount of taper increases the potential for a broadband performance starts to appear. This is evident with a 15% decreasing taper. It was observed that with this particular dipole plus EBG combination a decreasing taper in the vicinity of 20% has the best potential for success. Keeping that in mind simulations were performed where the dipole lengths were adjusted to improve the performance.

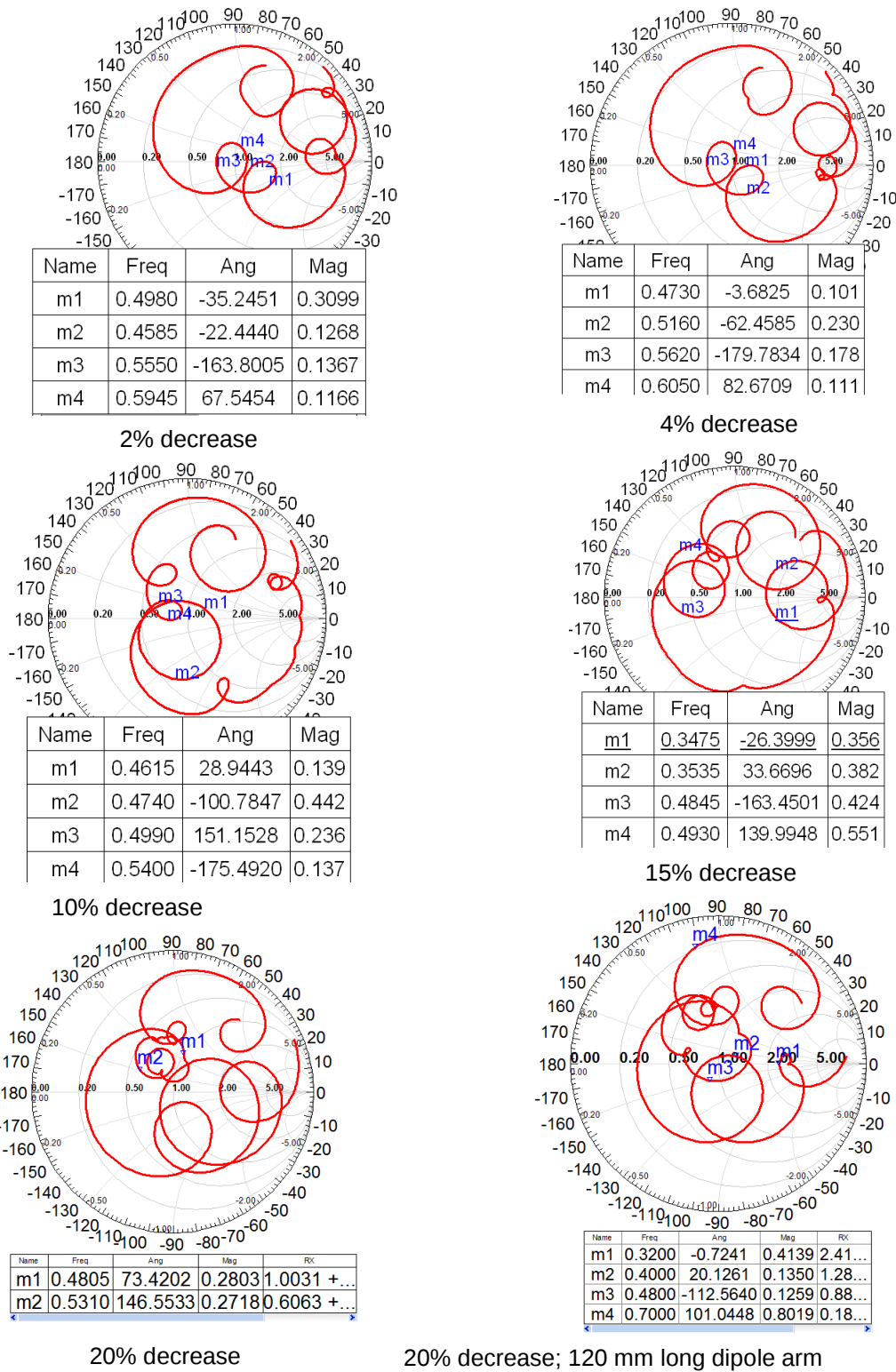


Figure 10. Simulated impedance vs. frequency of tapered EBG (decreasing taper) and fat strip dipole.

If the length of each arm of the dipole was reduced to 120 mm and a 20% decreasing taper was used the results shown in the last VSWR plot in Fig. 9 were obtained. The VSWR response shows clear potential for broad bandwidth extending from 320-680 MHz within $VSWR < 3:1$ which is more than an octave. Although in some regions across the frequency band the VSWR exceeds 3:1 it is expected that further tuning will reduce these numbers. Corresponding impedance vs. frequency characteristics are shown in Fig. 10.

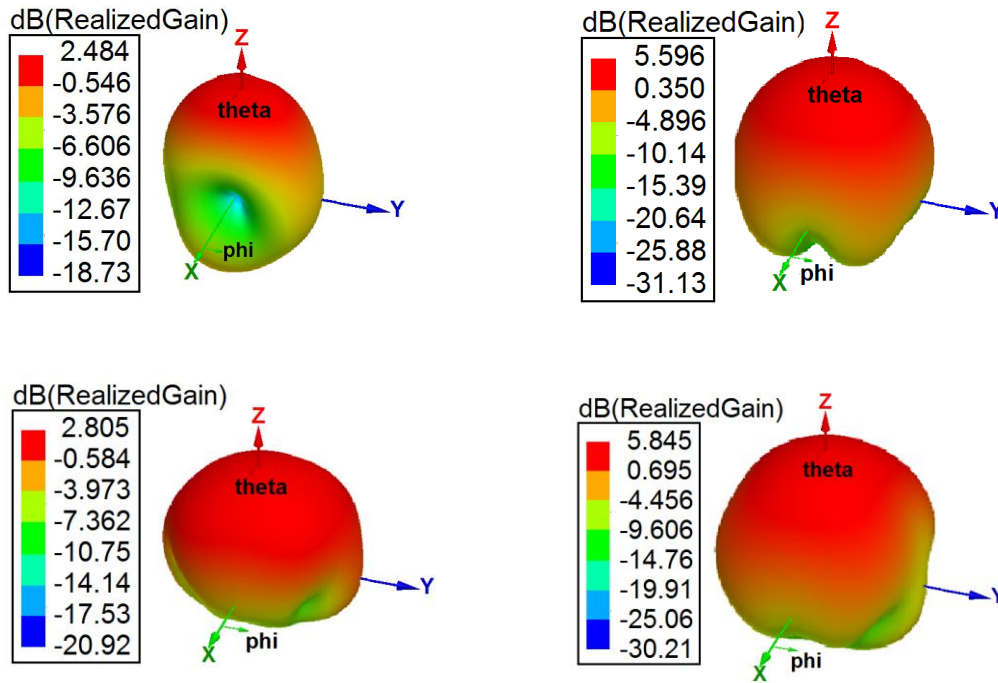


Figure 11. Simulated three-dimensional peak realized gain patterns at 319 MHz, 450 MHz, 550 MHz and 600 MHz.

Table 3: Simulated peak realized gain of the fat strip dipole on the tapered EBG. Each arm of dipole is 120 mm long and the EBG has a 20% decreasing taper.

Frequency (MHz)	319	400	450	500	550	600	650
Realized Gain (dBi)	2.48	-0.52	5.6	2.06	2.8	5.84	4.41
Directivity (dBi)	4.78	4.99	7.12	5.08	4.58	7.20	6.73

Simulated peak realized gain patterns (three-dimensional) are shown in Fig. 11. As apparent, patterns are directional. The peak realized gain numbers at various frequencies are listed in Table 3. The peak realized gain is greater than 2 dBi at all frequencies except at 400 MHz. The directivity at 400 MHz is high but the gain is near -0.5 dBi. This discrepancy needs further investigation.

Further evidence of improving matching/tuning is shown in Fig. 12 which shows that reasonable control on the VSWR response can be obtained by adjusting the height of the dipole from the EBG surface. Thus once the EBG design is complete the dipole lengths, widths, and the

dipole height can be adjusted to further improve the VSWR matching and or gain and pattern performance.

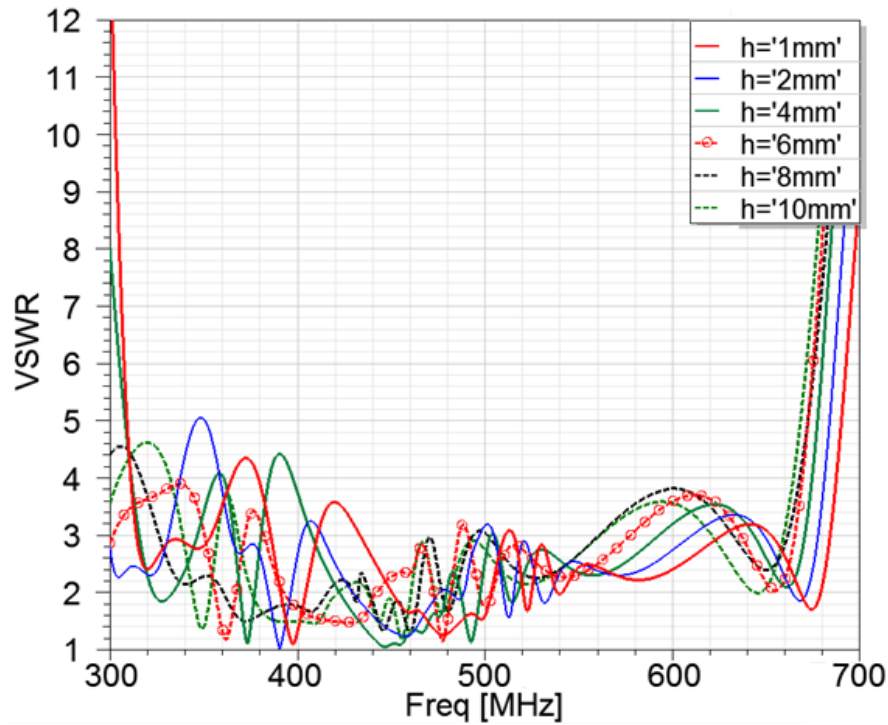


Figure 12. VSWR tunability of the broadband EBG plus antenna; h represents the height of the antenna from the EBG surface.

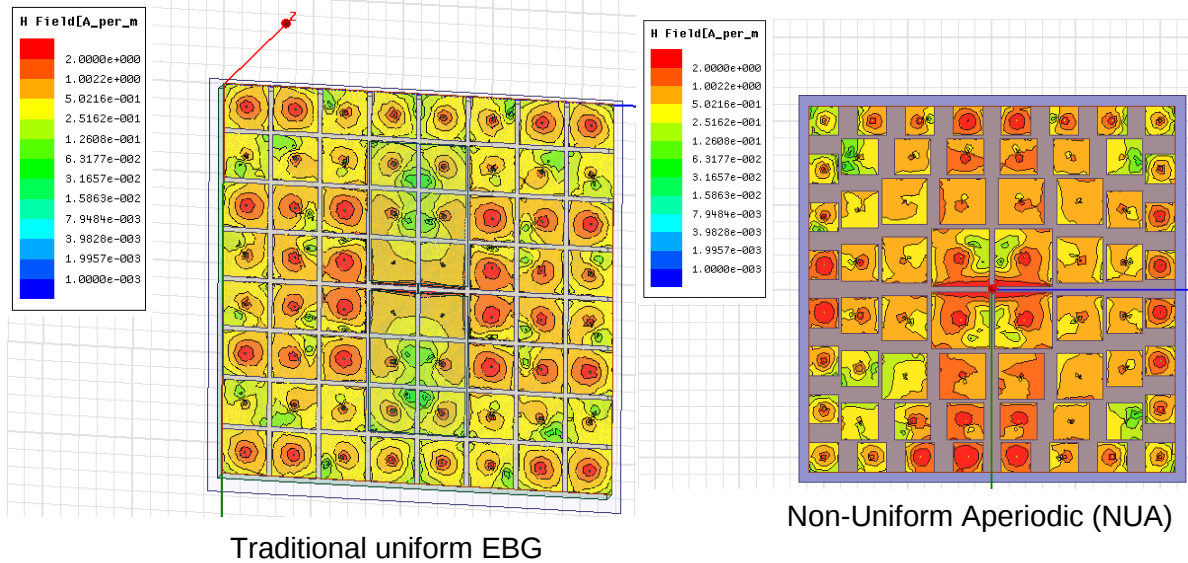


Figure 13. Simulated magnetic (H) field distributions on the EBGs.

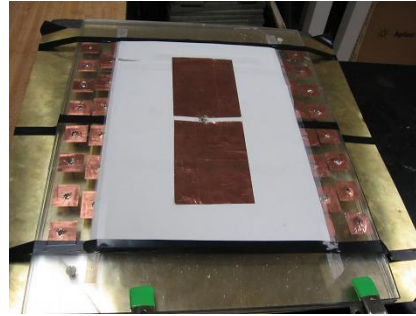
Comparing and contrasting the magnetic field distributions on the traditional uniform EBG and the proposed Non-Uniform Aperiodic (NUA) EBG (Fig. 13) it is clear that the NUA EBG is excited like a distributed radiating structure. Most likely the broadband performance is as a result of that.

3.4 Experimental Results

To validate the simulated performance the proposed NUA EBG was fabricated (Fig. 14). Due to the unavailability of thick FR4 materials 0.88 inch thick Plexiglas ($\epsilon_r=3.4$) was used as the substrate. A brass sheet was used to create the conducting ground plane. Each EBG patch was made from flexible copper tape. At the center of each EBG patch a hole was drilled and a 2 mm diameter copper wire was inserted. The copper wire was then soldered to the EBG patch and the brass ground below. The dipole antenna was also made from flexible copper tape and was fed using a coaxial cable. A surface mount chip balun [32] was used to excite the two dipole arms in a balanced manner.



NUA EBG top view



NUA EBG plus dipole

Figure 14. Photographs of the fabricated NUA EBG and the EBG plus the dipole antenna.

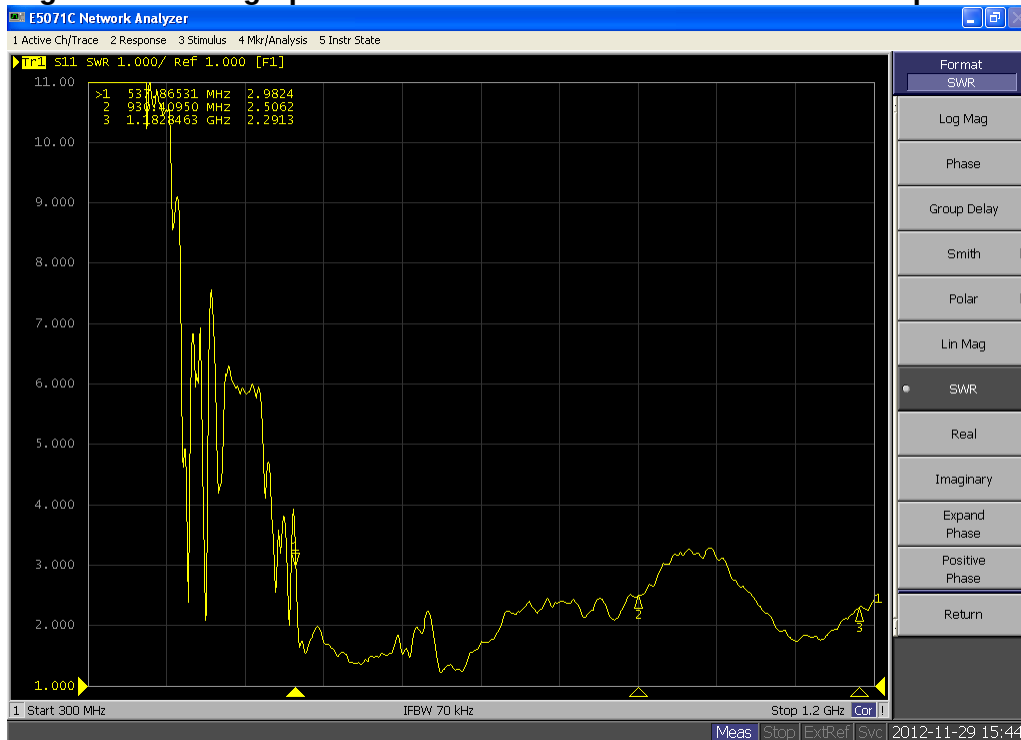


Figure 15. Measured VSWR vs. frequency characteristics.

Measured VSWR data of the above NUA EBG plus antenna are shown in Fig. 15. It is clear that the antenna operates from 537-1180 MHz within VSWR 3:1. The frequency shifted higher compared to the simulations because we used Plexiglas as opposed to FR4. Note that low frequency operation with Plexiglas can be obtained but in that case the EBG sizes and their inter-element separations need to be determined first. At present the EBG plus antenna is awaiting further characterizations.

4. Conclusion

The objective of this ARO STIR project was to investigate the feasibility of broadband multifunctional metamaterials. Starting from the study of a baseline uniform EBG metamaterial and a fat broadband dipole research investigations were carried out on various Non-Uniform Aperiodic (NUA) EBG metamaterials. The fundamental idea was inspired by the analogy of formation e.g. microwave filter design or broadband impedance matching where the elements of the ladder network are not the mere repetition of the same element. Instead the elements are determined by mapping the desired response with respect to a mathematical function such as the Chebyshev polynomials [33]-[35].

It was observed that if NUA EBG surfaces with a decreasing taper were illuminated by the near fields of fat dipoles the result was broad impedance and pattern bandwidth for the antenna. Although this is a specific case it is understandable that similar concepts can be applied to EBG metamaterials and other types of metamaterials if broad bandwidth is sought. Experimental measurements clearly demonstrate this potential. For example, with only about 1 inch thickness and no magnetic material loading or active device tuning a bandwidth more than an octave is attainable in the UHF frequency band. This is a very significant leap over existing state of the art.

Future research should focus on the development of the systematic theory and design guidelines for broadband EBG metamaterials or other types of metamaterials such as Frequency Selective Surfaces (FSS) that will address many critical problems in military communication and radar systems e.g. bandwidth, gain, thickness, weight, visual signature.

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