Mechanism of Apparent Gain Observed in Focused Beam Measurements of a Planar FSS

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Introduction

Apparent gain in focused beam measurements (tenths of a dB above 0 dB for calibrated VNA transmission) has been observed on many occasions for low loss resonant structures that include photonic/electromagnetic band-gap (PBG/EBG) structures [1] or frequency selective surface (FSS) stacks [2]. The authors are unaware of any previously published explanations perhaps due to the small magnitude of deviation. However, for a device with tight specifications, tenths of a dB deviation without explanation may be unacceptable, and transmission coefficient data greater than 0 dB can create controversy. This paper will demonstrate that the apparent gain seen in focused beam measurements occur due to radiation via mutual coupling from FSS elements not directly illuminated. Radiation from these elements increases the directivity of the stack resulting in an effective gain as measured by a VNA.

Focused Beam Measurements

Free-space focused-beam measurements have been successfully used to verify microwave electromagnetic performance of a variety of material samples [3] through vector network analyzer (VNA) measurements of transmission or reflection coefficients [4]. A focused beam system simulates plane-wave illumination of targets in a compact area using lenses to focus radiation in the form of a Gaussian beam. At the waist of a Gaussian beam the phase is planar while the amplitude is tapered to eliminate edge diffraction effects of a finite sized sample. For material samples that are planar and homogeneous a Gaussian beam illumination successfully simulates plane-wave illumination. Many inhomogeneous and anisotropic samples such as honeycomb can be successfully modeled assuming homogeneity by using an effective dielectric constant. However, homogeneity assumptions for material samples using structures of periodic elements, either metallic or dielectric, are sometimes inaccurate. One observed indicator is an apparent gain of a calibrated transmission coefficient measurement from a passive planar sample.

FSS interactions with an incident field

An FSS structure is a periodic array of metallic or dielectric elements shaped to provide particular interaction with incident radiation. These structures have found utility in radar cross section (RCS) reduction as frequency filters. For example, a broadband band-stop
filter designed to be transparent from DC to a cutoff frequency will reduce the RCS for hostile radar systems that operate within the band-stop region. This class of FSS is the demonstration subject for the increased directivity phenomenon in this paper.

Multilayer radomes using FSS sheets, referred to generally as stacks, can be designed assuming plane-wave illumination of a large or infinitely sized array. Stack design models using this strategy have the advantage of computational savings while providing a robust preliminary model of a realistic stack. An infinite design accurately models the behavior of the array except for the edge elements. For an infinite array, an incident plane-wave is said to interact with FSS elements according to the Floquet theorem which states that the induced element currents match both the amplitude and phase of the incident wave. Munk [5] explains this is only true for an infinitely periodic array. For a finite array, the Floquet theorem becomes only a first order approximation and additional currents are induced due to the finite size of the array through variable mutual impedances of the FSS elements. Mutual impedance is a measure of the interaction of closely spaced elements. A current in one element will induce a field in another element which in turn results in an impressed voltage as a function of the mutual impedance. Spacing of less than a half wavelength (which is common in FSSs to prevent grating lobes) are subject to significant mutual coupling. In addition, under Gaussian beam illumination; the elements outside of direct illumination are excited by parasitic coupling which is not modeled under plane-wave illumination assumptions.

![Figure 2 – 10x10 array of four-legged loaded loop type elements.](image)

**Description of the Simulation Parameters**

Figure 2 shows the geometry of the FSS array designed for the simulation. The elements as described by Munk [6] are group 2, four-legged loaded (metalized) loop type elements. A stack was designed with two layers of a 10x10 array on either side of a PTFE (Teflon) substrate and two foam matching layers on top and bottom. The element lattice separation is 0.4 inches making the array 4 inches square. This FSS stack was designed as a band-stop filter centered at approximately 8 GHz. To simulate the focused beam measurements, a Gaussian beam illumination with a beam-waist diameter of two inches was used. Computations on the FSS stack were performed by Ansoft HFSS™, a commercial finite element method (FEM) solver for electromagnetic structures. The key objective was to compare the transmission amplitude between plane-wave illumination
and Gaussian beam illumination. Normalization for each case was achieved by comparing the transmission through the stack to that of free-space, mimicking the approach used for focused beam measurements.

**Simulation Results**

Figure 3 is a comparison of the simulated FSS stack transmission coefficients versus frequency for each illumination type. As designed, the band-stop filter is transparent for frequencies 2-7 GHz and reflective in the stopband of 7-9 GHz (for normal incidence illumination). The dashed red plot identifies the transmission coefficient for the stack under plane-wave illumination. The transmission coefficient for the transparent frequency band is close to 0 dB. The solid black plot identifies the transmission coefficient for the stack under Gaussian beam illumination. The transmission coefficient averages approximately +0.3 dB in the transparent frequency band. The simulation results match what is observed during a focused beam measurement that cannot be presented herein.

![Figure 3](image-url)

**Figure 3 – Comparison of transmission coefficients for an FSS stack under both plane-wave illumination and Gaussian beam illumination.**

Figure 4 shows the magnitude of the E-field at a single moment in time for the Gaussian beam illumination case. The beam is incident from below the figure and travels up through the stack. The incident beam directly illuminates the six middle elements of the array. As expected the six middle elements are shown radiating with approximately the same amplitude and phase as the incident wave. An animation of this interaction shows that the four elements outside the direct illumination also radiate, but with a smaller amplitude and a time lag with respect to the inner elements. These elements are reradiating energy from adjacent elements by the mechanism of mutual coupling and not from direct illumination. A time domain plot of the transmission coefficient measured with a VNA would show a time spread of the received signal with respect to the transmitted signal confirming a time delay. The directivity of an array increases by either increasing the number of elements or increasing the spacing between the elements resulting in a larger aperture area. Mutual coupling to the parasitic elements increases the number of elements radiating from the stack increasing its directivity.
Figure 4 – Magnitude of the E-field for a Gaussian beam illumination of an FSS stack. Illumination is at 4 GHz, in the pass band of the FSS stack.

Conclusions

Computational simulations show that parasitic FSS elements radiate energy via mutual coupling from directly illuminated elements effectively increasing the directivity of the structure. The increase in directivity results in an apparent gain as measured during calibrated VNA measurements on a free-space focused beam system.

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References


