# Using Gaussian Optics Measurement System to Characterize A New Wideband Low-Loss Antenna-Slot-Antenna

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***Abstract*—A new type of unit cell featuring wideband low loss characteristics is proposed for transmit-arrays (TA) and frequency selective surfaces (FSS) in Quasi-Optical applications. The TA is realized as a non-uniform array of antenna-resonator-antenna (ARA) elements and the FSS is realized as a uniform array of ARA elements. Each ARA element is a three layer structure consisting of two patch antennas and a slot resonator. The ARA elementary cell is designed and verified using finite element method simulation. A free space Gaussian optics measurement system (GOMS) is utilized to characterize the elementary cell. The measurement results show a 20.7% -3dB (12.2% -10dB) bandwidth and a maximum in-band insertion loss of <0.2 dB for 42 GHz.**

## I. Introduction

Antenna-Resonator-Antenna (ARA) elements is composed of a receive antenna, a non-radiating resonant structure, and a transmit antenna operating between the input and output radiation ports [1]. These elements can be used for the Transmit-Array antennas (TA) [2], or to form Frequency-Selective-Surface (FSS) [3].

In general, these elements are formed as three layer metallic structures: two resonant type planar antennas in the top and bottom layers, and one or more planar transmission line resonators in the middle layer. Microstrip antennas and coplanar waveguide (CPW) resonator have been mostly used for the antenna-resonator-antenna elements to form either TAs [2] by non-uniform array or FSS by uniform arrays. Using ARA elements in the transmit-arrays results in a band-pass transfer function, whose band-pass characteristics are desirable for radar, satellite [4], and power combining applications [5], where the distributed nature of the transmit-arrays can improve the power-handling and heat dissipation in the structure.

In terms of wave optics, a convex lens can be described as a device that transforms a diverging input spherical wave into a plane wave at the output, or an input plane wave into a converging spherical wave at the output [6]. In a transmit-array, the wave transformation is achieved by modifying the received phase distribution through the phase-delay of the ARA elements. In an array with optimal cell size, the input-output phase-delay in each cell is a function of the frequency, and can be written in terms of the S-parameters of the ARA cell as follows:

$$\Phi_m(\omega) = -\angle S_{21}^m(\omega) \quad (1)$$

An accurate measurement technique is vital to the assessment of the design method. In particular, the ability to accurately measure both transmission and reflection coefficients is critical in identifying the design errors and fabrication imperfections.

Usually, the transmit-array and frequency selective surface unit elements are measured either by shining a large sample with a plane wave in the anechoic chamber [4], or by replacing a small sample in a waveguide and measuring the S-parameters [7]. The first method obviously requires a large sample, and normally does not provide a way to measure the reflection. The waveguide technique can measure the reflection, but it has two disadvantages. First, the cross-sectional dimensions of a standard waveguide are not generally integer multiples of the FSS grid period. Second, as full metallic waveguide cannot carry a TEM mode, it cannot be used to measure the sample at normal or arbitrary angles of incidence. An alternative approach is to use a free space measurement setup that simulates the guided system. This method will be detailed in section III.

This paper highlights our approach to the Antenna-Resonator-Antenna element design, as a three-layer structure consisting of two patch antennas and a slot resonator, and further discusses effective measurement methods that can be used to characterize it. Especially, we introduce a method to extract the focusing S-parameters of the ARA based on the Gaussian optics measurement system. The focus will be on FSS applications.

## II. ARA Structure & Basic Design

### A. Antenna-Resonator-Antenna concept

Fig. 1 shows a case where the radiative elements in the ARA are two back-to-back microstrip patch antennas, and the middle non-radiating slot resonators are fabricated in the common ground plane (referred to as the slot layer). The coupling between the antennas and the slot resonators is achieved through coupling slot in the ground layer.

The use of resonant-type radiative elements is advantageous, since a resonant element by itself can be considered as a combination of a radiative resistance and a resonator. The built-in resonators of the receive/transmit antennas can then be combined with the slot resonant structure to form a band-pass filter between the radiative ends Fig. 2.

The parameters in the antenna circuit model can be extracted from the simulation of the antenna and the coupling slot in an infinite structure, or in a periodic array with a cell size of 3.6 mm which is determined from the effective radiative aperture of the antennas [8]. The real design parameter after fixing the antenna and the slot line dimensions, is the value of coupling between the antennas and the resonator, and this is controlled by the position of the coupling slot relative to the center of the patch. The proposed circuit model is only valid for a normal incident wave with the electric field polarized in parallel to the slot resonator.

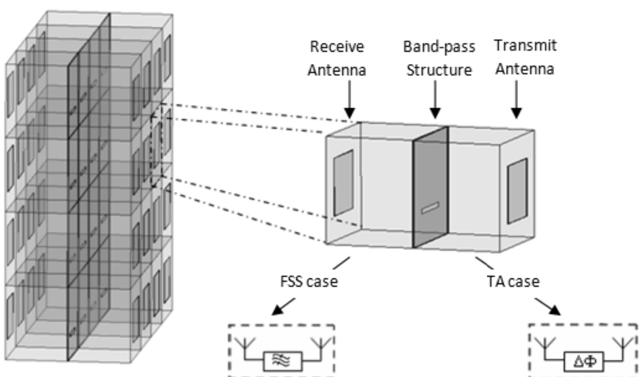
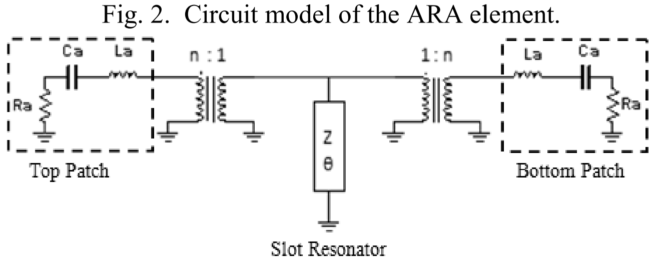



Fig. 1. An ARA array composed of patch antennas and slot resonators.

Fig. 2. Circuit model of the ARA element.




## B. Antenna-Resonator-Antenna Circuit Model

This section describes the general considerations in design of the radiative elements and coupling slots. According to the circuit model shown in Fig. 2, the input/output coupling of the unit cell are related to the external $Q$ ($Q_{ext}$) of the end resonators [9], which for a resonant patch element can be written as [10]:

$$Q_{ext} = Q_r = 2\pi f_0 \frac{W}{P_r} \tag{2}$$

Where $f_0$ is the resonant frequency, $W$ is the total stored electromagnetic energy, and $P_r$ is the radiated power. Neglecting the losses in the antenna, $Q_{ext}$ can be written in the following form:

$$Q_{ext} = 2\pi f_0 \frac{L_a}{R_a} \tag{3}$$

Where $L_a$ and $R_a$ come from the series RLC model of the antenna (see Fig. 2). In the case of patch antennas, the substrate thickness is particularly important in achieving the desired value of $Q_{ext}$: the thicker the substrate, the lower $Q_{ext}$ and the wider the pass-band.

All components of this model are calculated using analytical expressions taking into account the physical parameters of the structure [2].

## C. Antenna-Resonator-Antenna Design

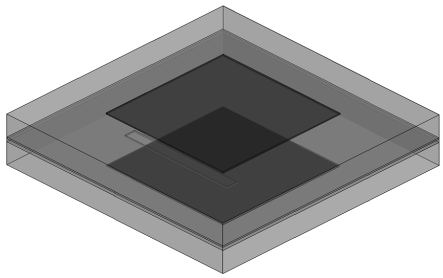
The elementary cell is represented in Fig. 3. It consists of a single ground plane, two substrate layers (Rogers RT/duroid 5880, $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$, thickness 315µm) and two patch antennas coupled by a slot in the ground plane. This cell can be used in uniform array for FSS applications (Q-Band), and can also be used in non-uniform array for TA applications (Satellites). The two transmission phase values with a 180° phase difference (1-bit compensation) are obtained by flipping one of the patches with respect to the coupling slot. The patch and cell sizes equal 1.95×1.95 mm² and 3.6×3.6 mm² ($\lambda_0/2\times\lambda_0/2$), respectively.

The size of the linear line slot in the ground plane is designed for a good matching for 42 GHz which corresponds to wavelength in the substrate $\lambda_g$. The line slot size equal 1.7×0.16 mm². This elementary cell is a single polarization design. An incident wave with the appropriate polarization is received by the first patch antenna in the input side, passes through the line slot resonator, and reradiates from the second patch antenna with the same polarization.

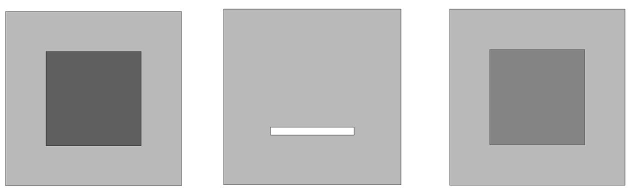
Design and optimization of the element is relatively straightforward and converges after a handful of iterations, by hand-waving between circuit and finite-elements models.

An in house CAD tool has been developed to design and evaluate the performance of transmit-arrays, starting from the electromagnetic characteristics of the elementary cell and incident wave or the focal source. The radiation pattern of the feed is first used to determine the electric field distribution illuminating the first antenna array. The radiation patterns and S-parameters of each elementary cell are then used to compute the radiation pattern, gain and directivity of the transmit-array.

In the case of transmit-array, the main design challenge is the ability to generate the appropriate phase-shift for each cell in order to transform the incoming spherical wave on the free-space side, i. e. to produce a nearly-flat phase distribution or a given phase gradient depending on the main beam direction.



(a)



(a) (b) (c)

Fig. 3. ARA element based on patch antennas and slot resonatot; a) 3D structure, b) top layer, c) middle layer, d) bottom layer.

## III. FREE-SPACE MEASUREMENT SYSTEM

### *A. Measurement Method*

The alternative approach to the two measurement methods highlighted in section-I, is to use a free space measurement setup that simulates the guided system. Quasi-optical measurement systems have been used for this purpose by a number of researchers [11] for performing similar measurements at 60-300 GHz. However, the required lens/mirror size and focal length prove impractical at Q-band.

Based on the hard-horn developed by Ali et. al, [12], a guided measurement system can be developed to simulate an oversized parallel-plate waveguide. Hard-horns are antennas with nearly uniform aperture distribution, which are formed by dielectric loading of the metallic pyramidal horns. A specially designed dielectric lens is used at the aperture to compensate the spherical phase error across the aperture. The hard-horns act as a matched transition between the coaxial terminals and the oversized TEM waveguide ports. The sample under test can be sandwiched between two of these waveguide ports, to form a guided system with coaxial ports.

This system has been successfully used for excitation and measurement of Ka-band quasi-optical amplifier arrays [13]. Although in our application it is impractical to sandwich the FSS sample between the two hard-horns, due to the loading effect of the dielectric lenses, still the hard-horns can be used to form a quasi-guided system.

In the modified system, which is shown in Fig. 4, the hard horns form two parallel TEM ports that are separated by an air gap, and the sample under test is placed in the middle of two ports. Due to their high directivity, the hard-horns are expected to generate a good approximation of the plane wave in the near-field, as is required for the FSS/TA measurements. As the sample can be freely reoriented in the air gap, the quasi-guided system proves convenient for performing measurements at arbitrary angles of the incidence. However, the oblique incidence measurement generally requires larger samples and a wider air gap.

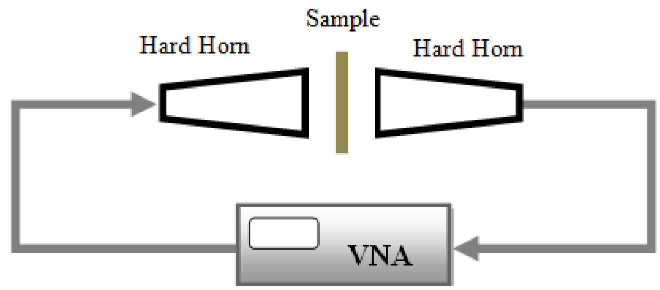



Fig. 4. The free-space measurement system using hard horns.

Since the electromagnetic field in the gap region is assumed to be predominantly TEM, the air gaps between the hard horn apertures and the surface of the sample can be treated as transmission-line sections. This allows for a standard TRL (Thru-Reflect-Line) calibration of the measurement setup, which simultaneously de-embeds the connecting cables, hard-horns, and air gaps, from the measurement [14]. Also a time-gating process is applied, to filter out the residual error due to the multiple reflections of the high-order modes.

Fig. 5 shows ARA in a Gaussian optics measurement system. An input axial beam of the waist radius $\omega_{01}$ is generated using a transmit horn antenna. The waist of the input beam is located near the phase-center of the horn and at a distance $z_1$ from the center of the ARA. The output is a Gaussian beam with the waist of radius $\omega_{02}$ at a distance $z_2$ from the center of the ARA. An open-ended waveguide antenna is used to probe the output radiation intensity along this axis. Reference [15] gives more details about the analytical formulae used to find the different parameters of the measurement setup shown in the Fig. 5.

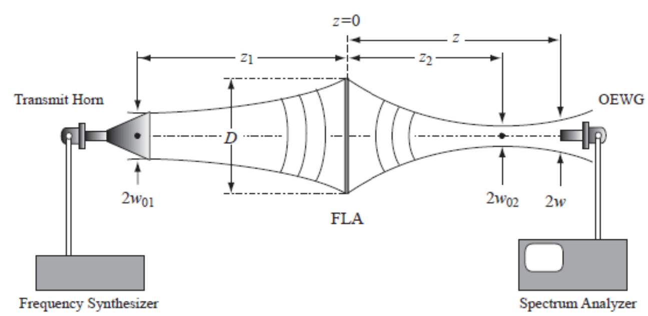



Fig. 5. ARA in a Gaussian optics measurement system [15].

### *B. Experimental Results*

The measurement setup, described in the previous section, is based on Agilent 8510c vector network analyzer and the hard horns. The hard horns are used as transitions between coaxial input/output and planar wave fronts. A TRL calibration is applied to eliminate the effects of cables, connectors, hard horns, and the air gap between the hard horn apertures and the

FSS samples. The measured reflectance, transmittance, and transmission phase are shown in Fig. 6, along with the simulation results. The measurement results show a 20.7% -3dB bandwidth for 42 GHz (12.2% -10dB), the maximum in-band insertion loss for this design is <0.2 dB. Fig. 6 confirms a very good agreement between simulations and experiments (GOMS).

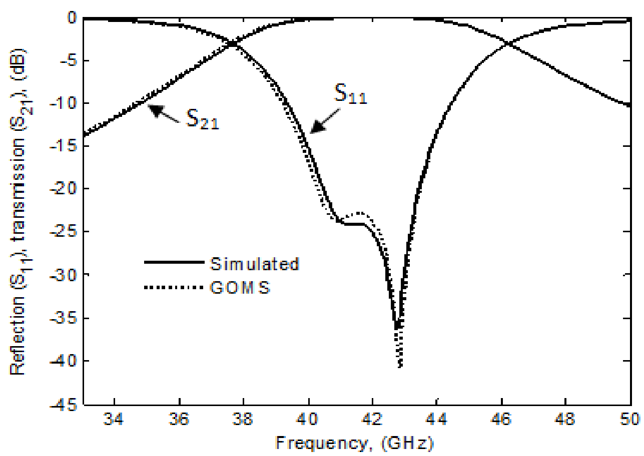



Fig. 6. S-parameters of the ARA element, measurement by Gaussian optics measurement system (GOMS) and simulation.

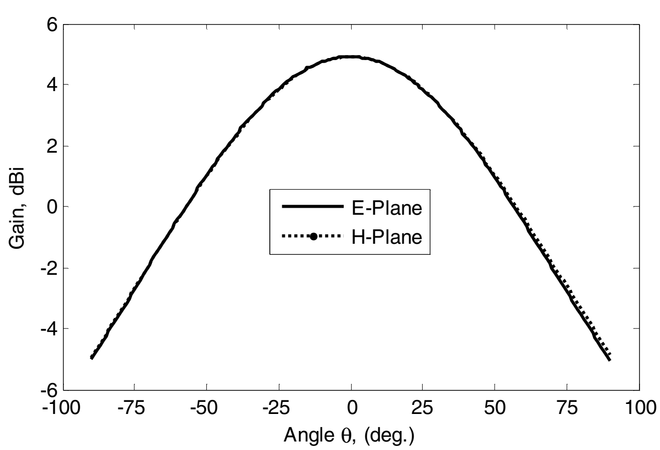



Fig. 7. The radiation pattern of the ARA element computed at 42 GHz. This computation is done with periodic boundary conditions on thes sides. This radiation pattern shows a maximum gain of 4.9 dBi and a -3dB beamwidth of 86° in E-Plane.

## IV. CONCLUSION

High-efficiency wideband antenna-resonator-antenna elements can be designed using patch antennas and slot resonators. A uniform array of these elements features low-loss and wideband, which makes it an excellent candidate for frequency selective surfaces and filtering applications in quasi-optical amplifier arrays. Detuned versions of the proposed element can also be used to form other types of beam-formers. This ARA element is adequately characterized in non-anechoic environments by using the Gaussian optics measurement system. The experimental results are in good agreement with the simulation in terms of impedance matching and insertion loss. Two other cells are currently under investigation by the authors to design novel reconfigurable discrete lens antennas for high-speed wireless communication.

## REFERENCES


[1] H. Kaouach, L. Dussopt, R. Sauleau, and Th. Koleck, "Deign and demonstration of an X-band transmit-array," 3rd European Conference on Antennas and Propagation, Berlin, Germany, EuCAP, March 2009.

[2] H. Kaouach, L. Dussopt, J. Lanteri, R. Sauleau, and Th. Koleck, "Wideband Low-Loss Linear and Circular Polarization transmit-Arrays in V-Band," IEEE Trans. on Antennas and Propagation, Vol. 59, No. 7, pp. 25132523, July 2011.

[3] R.M.S. Cruz, A. G. Assuncao, and P. H. F. da Silva, "A new FSS design proposal for UWB applications," International workshop Antenna Technology (iWAT), Lisbon, Portugal, March 2010.

[4] H. Kaouach, L. Dussopt, R. Sauleau, and Th. Koleck, "Design and demonstration of 1-bit and 2-bits transmit-array at X-Band frequencies," 39th European Microwave Conference, Rome, Italy, Sept. 2009.

[5] M. P. DeLisio, and R. A. York, "Quasi-Optical and Spatial Power Combining," IEEE Transactions on Microwave Theory and Techniques, Vol. 50, No. 3, March 2002.

[6] B. E. A. Saleh and M. C. Teich, "Fundamentals of Photonis," John Wiley and Sons, Hoboken, NJ, 1991.

[7] A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and Ph. Pouliguen, "1-Bit Reconfigurable Unit Cell Based on PIN Diodes for Transmit-Array Applications in X-Band," IEEE Trans. on Antennas. and Propagation, Vol. 60, No. 5, pp. 2260-2269 May 2012.

[8] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, "Microstrip Antenna Design Handbook," Artech House, Boston, MA, 2001.

[9] G. L. Matthaei, L. Young, and E. M. T. Jones, "Microwave Filters: Impedance-Matching Networks, and Coupling Structures".

[10] R. S. Elliott, "Antenna Theory and Design, Revised Edition," John Wiley and Sons, Hoboken, NJ, 2003.

[11] B. C. Deckman, "Active Quasi-Optics and Measurements," Ph.D. thesis, California Institute of Technology, Pasadena, CA.

[12] M. A. Ali, S. C. Ortiz, T. Ivanov, and A. Mortazawi, "Analysis and measurement of hard-horn feeds for the excitation of quasi-optical amplifiers," IEEE Trans. Microwave Theory Tech., vol. 47, pp. 479−487, April 1999.

[13] S. C. Ortiz, J. Hubert, L. Mirth, E. Schlecht, and A. Mortazawi, "A high-power Ka-band quasi-optical amplifier array," IEEE Trans. Microwave Theory Tech., vol. 50, pp. 487−497, Feb. 2002.

[14] G. F. Engen and C. A. Hoer, "Thru-reflect-line: an improved technique for calibrating the dual six-port automatic network analyzer," IEEE Trans. Microwave Theory Tech., vol. 987-993, pp. 27, Dec. 1979.

[15] A. A.Tamijani, "Novel Components for Integrated Millimeter-Wave Front-Ends," Ph. D. Thesis, in The University of Michigan 2004.