Planar Antenna Arrays for Ku/Q Bands

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Final Report 2000-2001 for MICRO Project 00-041
Industrial Sponsor: Rockwell Science Center

ABSTRACT

In this report, the issue of mutual coupling between quasi-Yagi elements of a novel dual-band phased array structure is investigated. While the coupling between two $\lambda_0/2$-spaced quasi-Yagi elements is reasonably low (-25 dB in E plane, -20 dB in H plane) in its original design, it is found that the coupling levels can be pushed to below –30 dB in both planes by cutting a slit in the dielectric in the E plane and adding a metal fence in the H plane. This makes it possible to realize full 2D phased arrays which are free of scan blindness over a wide range of frequencies and scan angles. Based on these findings, a K-band 4-element passive linear array has been constructed. The measurement results show 38 % operating bandwidth for K band (SWR<2) and good radiation profiles.

1. INTRODUCTION

Modern satellite communications systems require multi-band, multi-beam array antennas to achieve large service area coverage, efficient power consumption, and high data transmission capacity. Active phased arrays offer the most cost-effective solution to the stringent requirements of modern satellite communications systems, since they are capable of forming thousands of beams from a single aperture simultaneously or on a time-sharing basis. They provide power-sharing among beams through distributed amplification, and in addition offer graceful degradation since the array can endure random failures of up to a significant portion of its T/R modules before performance degradation becomes noticeable [1].

The choice of array architecture is determined by several factors such as bandwidth, gain, efficiency, scan angle, volume, weight, and cost. Choosing the appropriate radiating element is one of the most crucial issues because the physical structure and EM characteristics of the antenna will determine the achievable performances of the entire system. Planar printed-antennas such as microstrip patches, dipoles, slots, bow-ties and spirals are used to construct arrays for various applications, although severe design trade-offs have been made in all existing designs. Recently we developed a planar quasi-Yagi antenna, which has several unique features including compact size, high efficiency, broad bandwidth, low sidelobes and low cross-polarization [2][3]. The most salient feature is that it can be fabricated on high permittivity substrates such as GaAs and InP, making it possible to integrate the antenna elements and MMIC T/R modules in a monolithic fashion. This approach should greatly improve the overall system efficiency, especially at millimeter-wave frequencies where most printed antennas such as microstrip patches have poor radiation efficiency.

One major concern in designing wideband, wide scanning angle phased arrays is scan blindness caused by mutual coupling between radiating elements. From this point of view, the issue of mutual coupling between quasi-Yagi elements to ensure scan-blindness-free construction is first investigated. Then, under the consideration of a mutual coupling issue, a K-band four-element quasi-Yagi array prototype has been designed.

2. ARRAY BANDWIDTH VS. MAXIMUM SCAN ANGLE

Normally the basic array architecture is chosen according to the type of antenna element used. For broadside elements, this means a tile-type array while for endfire elements, one can use a brick-type layout based on stacking “cards” of endfire radiators. Two major design parameters associated with a phased array are its frequency bandwidth and maximum scanning angle. To achieve broadband performance it is very tempting to use ultra wideband radiating elements such as the spiral or tapered slot. However, using a wideband element may not necessarily result in wideband performance of the overall phased array [4]. This is mainly because wideband elements usually have large physical sizes, and the overlapping between elements will greatly limit the bandwidth as well as maximum scanning angle of the phased array.

A preliminary evaluation indicates that the quasi-Yagi antenna offers one of the best tradeoffs in this regard. Fig. 1 shows the schematic of a 2D phased array based on the quasi-Yagi structure. Fig. 2 is the projected array bandwidth vs. maximum scan angle of the quasi-Yagi array in comparison with those based on existing wideband radiating elements including the spiral, sinuous and foursquare antenna [4]. Due to the extreme compactness of the quasi-Yagi element, it is possible to construct 2D arrays without grating lobes over the entire 50 % bandwidth. This indicates the quasi-Yagi antenna is capable of delivering the best combined performance in terms of overall array bandwidth (not element bandwidth) and maximum scanning range.

The above evaluation does not include the important factor of mutual coupling between antenna elements within the array. When two adjacent elements approach each other, the mutual coupling level may increase significantly and cause the notorious scan-blindness problem. This effect may further limit the maximum scanning angle of the phased array. As will be shown below, the quasi-Yagi antenna fortunately demonstrates very low mutual coupling even without any modification of the original design. This makes it possible to construct a 2D array free of scan blindness over the entire frequency range for scan angles as shown in Fig. 2.

3. E PLANE MUTUAL COUPLING AND MITIGATION

The mutual coupling between two neighboring quasi-Yagi elements in the E plane has been investigated experimentally for the X-band quasi-Yagi prototype [3]. Fig. 3 shows the picture of two side-by-side antennas with half-wavelength (15 mm) spacing at the center frequency of 10 GHz. It was found that the coupling level (S_{21}) is quite low across X-band from 8 to 12 GHz, even in the presence of the edge effect, with a peak S_{21} of –18.5 dB at 12 GHz. By attaching two small pieces of absorbers to the two side edges of the array to emulate two elements in a large array environment, the coupling level drops even further, with a maximum value of –22.4 dB at the upper end of the entire X band (solid line in Fig. 4).

To further reduce the mutual coupling, we propose cutting a slit in the dielectric substrate as shown in Fig. 3. The effect of the slit on mutual coupling was first simulated using our FDTD code [5]. From the simulation results, we confirm a narrow (1.2 mm) slit is sufficient to push the mutual coupling to the –30 dB level around the center of the frequency band. The above prediction has been confirmed with the measurement results shown in Fig. 4. The 1.2 mm slit reduced the coupling level by a few dB, from –26 dB to –30 dB at 10 GHz. The effect of the slit is not significant at both ends of the frequency band, as predicted in FDTD simulations.

4. H PLANE MUTUAL COUPLING AND MITIGATION

The quasi-Yagi antenna is basically a dipole-like radiator, although it has much wider bandwidth (>50 %) due to the unique and optimal design of the microstrip ground plane reflector as well as the parasitic director. Due to the typically wider H-plane radiation pattern of a dipole-based radiator, the mutual coupling between array elements in the H plane is a more serious concern in designing a full 2D phased array. A preliminary measurement indicated that the H plane mutual coupling between two half-wavelength-spaced quasi-Yagi elements could reach –17 dB at the lower end of the X-band [6], which may raise concerns about possible scan blindness in the H plane.

We have measured the mutual coupling between quasi-Yagi antennas in the H plane with $\lambda_0/2$ spacing. In the absence of edge effects, the measured results indicate that the coupling level is about –20 dB at the center frequency, and slightly higher at the lower end due to reduced electrical distance between the two antennas. This is shown by the solid curve in Fig. 6. Compared to the result in Fig. 4, the mutual coupling level in the H plane is about 5~6 dB higher near the center frequency, which is consistent with expectations. For applications that do not require very wide scan angles, the array spacing can be increased slightly (e.g., 0.7~0.8 λ_0). This should push the mutual coupling to lower levels, and also reduce the number of linear sub-arrays required to achieve a specific array gain.

In order to reduce the H-plane mutual coupling further for the case of half-wavelength array spacing, we have studied the schematic shown in Fig. 5, where a metal fence is inserted in-between the two quasi-Yagi antennas. To prevent the excitation of parallel-plate waveguide modes, two metal posts are used to connect the microstrip ground planes of the two antennas and the metal fence so that they are all kept at the same ground potential. As shown by a measurement result in Fig 6, adding the metal fence can greatly reduce the mutual coupling in the H plane. The measured coupling level at 10 GHz is –39 dB with the fence, compared to –20 dB without the fence.

5. K-BAND PASSIVE LINEAR ARRAY

A four-element passive array prototype covering K-band (20 GHz) has been constructed, as shown in Fig. 7. A prototype K-band array is designed for high dielectric Duroid substrate with a dielectric constant ε_r = 10.2 and a substrate thickness of 10 mils. The prototype has a compact dimension of 40 mm by 15 mm. The antenna design can be easily adopted to use GaAs or InP substrates for monolithic integration of the antenna arrays and MMIC T/R modules. The equal amplitude is realized using a simple corporate feed with binary dividers composed of T-junctions and quarter-wavelength transformers. The element spacing is set at half wavelength based on the preceding mutual coupling considerations. The designed array provides a main beam toward the broadside direction of the quasi-Yagi elements. Fig. 8 shows the measured return loss (S11). The bandwidth of four-element array is slightly decreased from that of the single element, about 38 % for K-band operation, due to the bandwidth of the feed network, when SWR < 2. The radiation pattern of the four-element array at 20 GHz has also been measured as plotted in Fig. 9. The cross polarization in the main beam is better than –15 dB. In addition, the first sidelobe level is better than –12 dB. These results are reasonable compared to the previous research of an X-band eight-element quasi-Yagi array [6].

6. CONCLUSION

Both simulation and measurement results of E- and H-plane mutual couplings between quasi-Yagi elements indicate that with proper design consideration, it is possible to construct a scan-blindness-free, fully 2D phased array using the planar quasi-Yagi radiating element which delivers optimal array bandwidth and maximum scan angle. Based on the ensured $\lambda_0/2$ center-to center spaced arrangement of elements, the developed four element array provides broadband operation and good radiation characteristics in terms of front-to-back ratio and cross polarization in FDTD simulation results. Further investigation including Q-band arrays is ongoing. The salient feature that the antenna is built on high permittivity substrate is attractive for monolithic integration with RF front-end circuitry such as GaAs or InP LNAs, which should greatly improve the overall efficiency of active phased arrays for high frequency applications.

INFORMATION ON PROJECT

-Takahide Nishio: 2nd year Ph.D student, one year.

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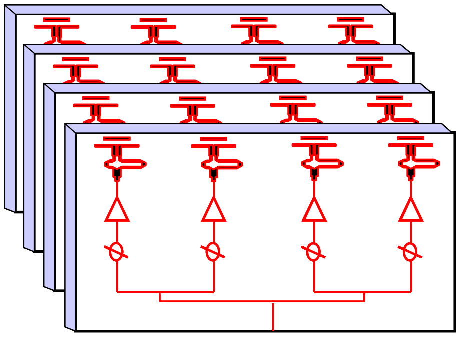

Fig. 1 Schematic of a 2D active phased array based on planar quasi-Yagi antennas.

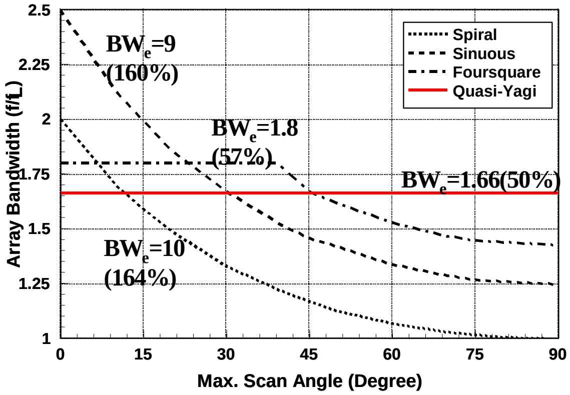

Fig. 2 Projected array bandwidth vs. maximum scan angle of the quasi-Yagi array and those using other wideband radiating elements.

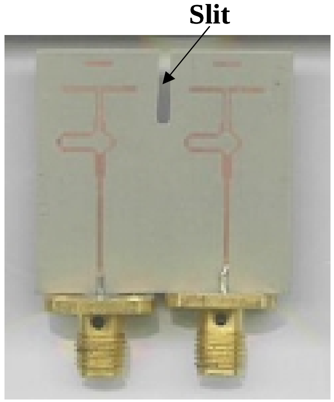

Fig. 3 Two-element quasi-Yagi array for E plane mutual coupling measurement.

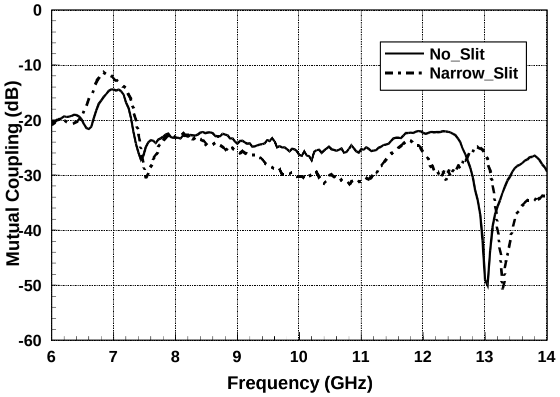

Fig. 4 Measured results of the effect of the slit on E-plane mutual coupling.

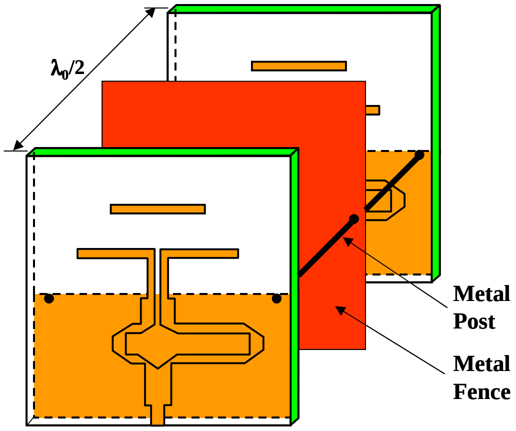

Fig. 5 Reducing H-plane coupling between quasi-Yagi antennas using a metal fence.

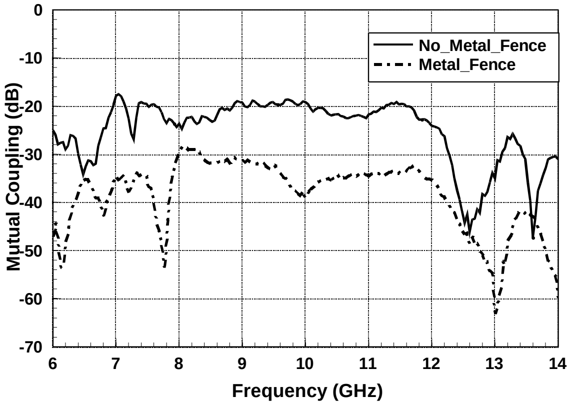

Fig. 6 Measured H-plane mutual coupling with and without the metal fence.

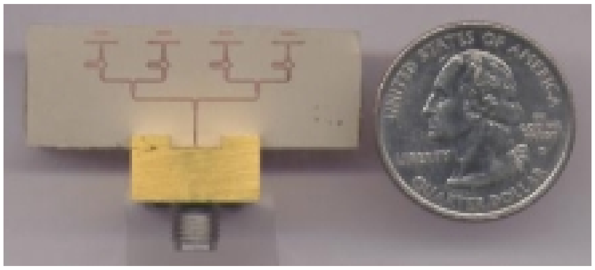

Fig. 7 Photograph of K-band four-element quasi-Yagi array prototype.

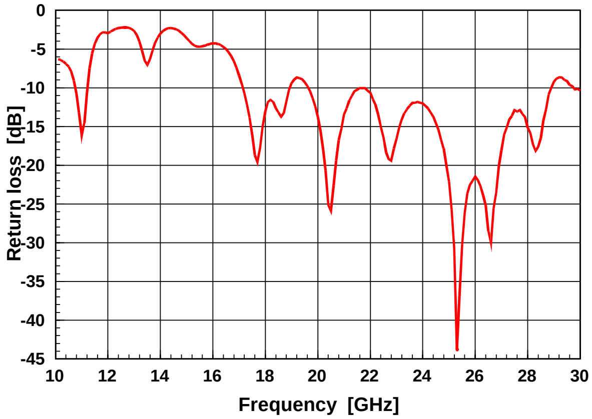

Fig. 8 Measured input return loss of the K-band four-element array at 20 GHz.

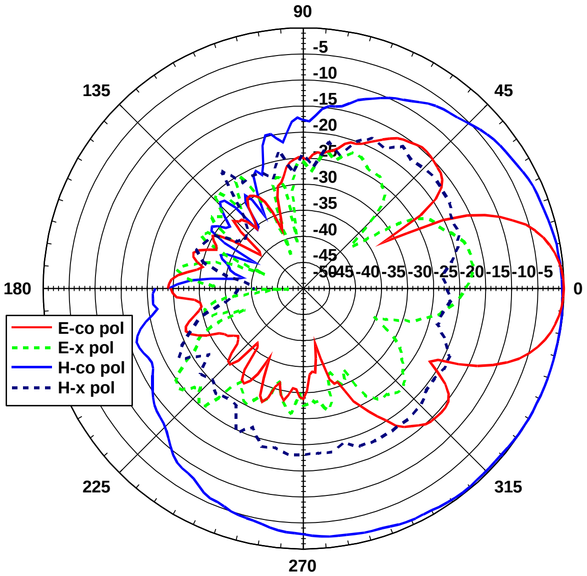

Fig. 9 Measured radiation pattern of the K-band four-element array at 20 GHz.