A New Quasi-Yagi Antenna for Planar Active Antenna Arrays

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***Abstract*—In this paper, a novel broad-band planar antenna based on the classic Yagi–Uda dipole antenna is presented, and its usefulness as an array antenna is explored. This "quasi-Yagi" antenna is realized on a high dielectric-constant substrate, and is completely compatible with microstrip circuitry and solid-state devices. This antenna achieves a measured 48% frequency bandwidth for voltage standing-wave ratio < 2, better than a 12-dB front-to-back ratio, smaller than -15 dB cross polarization, and 3–5-dBi absolute gain. Mutual coupling of the antenna in an array environment is investigated. Finally, three simple arrays are presented, demonstrating the usefulness of the antenna as an array element. This novel antenna should find wide application in wireless communication systems, power combining, phased arrays, and active arrays, as well as millimeter-wave imaging arrays.**

***Index Terms*—Planar antennas, quasi-Yagi antenna, spatial power combining.**

I. Introduction

ARRAY antennas in today's communications systems must be cost effective, yet highly flexible. Designers are increasingly being drawn to planar antennas because of their low profile, low cost, light weight, and their ease of integration into planar arrays. These antennas are highly compatible with solid-state electronics with the potential for very attractive solutions for phased-array antennas, power-combining arrays, and multiple-beam communications antennas. In this paper, we present a new planar antenna array element based on the classic Yagi–Uda dipole antenna, which we refer to as a quasi-Yagi antenna, and apply this antenna to several simple arrays.

Existing antennas for planar arrays suffer from a variety of disadvantages. Microstrip patch antennas are typically narrow-band and have relatively low efficiency due to an undesired substrate mode excited if high dielectric-constant substrates are used [1]. Although broad-band performance can be achieved by using more complicated schemes, such as the aperture-coupled patch antenna [2], these multilayer designs add to the complexity in the antenna configuration and manufacturing difficulties, as well as degraded backside radiation. The efficiency of the patch antenna can be also improved by chemical etching of the substrate at the expense of additional fabrication cost [3]. Slot antennas with either microstrip or coplanar waveguide (CPW) feeding offer wider bandwidth, but require additional design considerations and structural complexity such as using cavities or reflectors to overcome the problem of bidirectional radiation [4]. Alternatively, endfire antennas such as the Vivaldi and linearly tapered slot antenna (LTSA) are traveling-wave-type structures that can achieve broad instantaneous bandwidth [5]. However, they usually have larger electrical size than resonant-type patches or slots and often suffer from the excitation of substrate modes, which can result in reduced efficiency, strong crosstalk between antennas in an array environment, and perturbed radiation patterns. Antennas on high-permittivity electrically thick substrates can suffer from substantial problems with undesired substrate modes [6]. Additionally, tapered slot antennas also require either microstrip-to-slot or CPW-to-slot transitions as part of the feeding network, which not only increases the design complexity but also imposes a limit on the frequency response.

The Yagi–Uda antenna, first published in an English language journal in 1928 [7], has been used extensively as an endfire antenna. However, only limited success has been achieved at adapting this antenna to microwave/millimeter-wave operation. We have recently proposed and demonstrated a novel uniplanar quasi-Yagi antenna that has both the compactness of resonant-type antennas and broad-band characteristics of a traveling-wave radiator. The antenna was first demonstrated by Kaneda *et al.* [8] and further optimized for increased bandwidth [9]. The antenna is realized on a high dielectric-constant substrate with a microstrip feed. Unlike the traditional Yagi–Uda dipole design, we employ the truncated microstrip ground plane as the reflecting element, thus eliminating the need for a reflector dipole, resulting in a very compact design ($< \lambda_0/2$ by $\lambda_0/2$ for entire substrate) compatible with any microstrip-based monolithic-microwave integrated-circuit (MMIC) circuitry.

The quasi-Yagi antenna has several advantages over more traditional wire antennas radiating in free space. First, the presence of the substrate provides mechanical support for the antenna and planar transmission-line compatibility. Wire-type antennas in free space are extremely fragile at high frequencies and difficult to feed. Secondly, use of a high-permittivity substrate means that the antenna will be extremely compact in terms of free-space wavelengths. As will be shown in this paper, a center-to-center array spacing of $\lambda_0/2$ is easily achieved with this antenna, where λ_0 corresponds to a free-space wavelength at the center frequency of the antenna. Even tighter spacing may be achieved at the cost of increased mutual coupling.

In this paper, we present detailed information on the design and performance of a broad-band quasi-Yagi antenna, as well as

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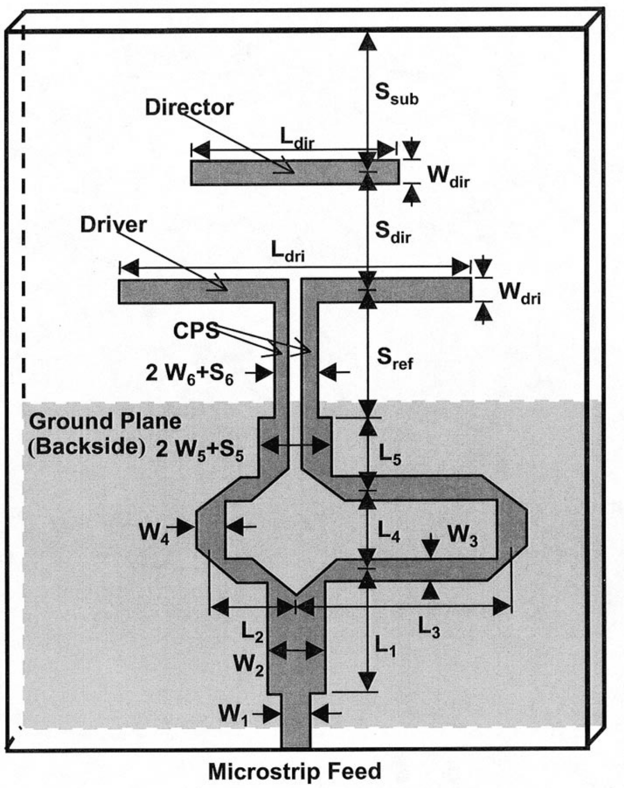


Fig. 1. Schematic of the quasi-Yagi antenna.

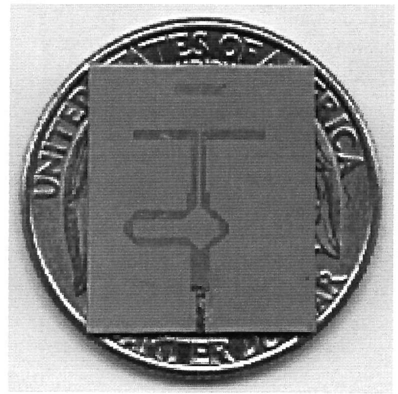


Fig. 2. Photograph of an X-band quasi-Yagi antenna.

its performance in an array environment. We have achieved extremely broad bandwidth (measured 48% for VSWR <2), good radiation profile (front-to-back ratio >12 dB, cross polarization < -12 dB), and moderate gain (3–5 dBi). It should be noted that the qualities are maintained across the entire matched bandwidth. Furthermore, the mutual coupling between neighboring elements of a quasi-Yagi antenna array is found to be very low, as will be discussed in more detail in Section III. Finally, several simple arrays are presented, which demonstrate the usefulness of the quasi-Yagi antenna as an array element.

II. Quasi-Yagi Antenna

Fig. 1 shows the layout of the uniplanar quasi-Yagi antenna. The antenna is fabricated on a single substrate (0.635-mm-thick Duroid $\varepsilon_r = 10.2$ for the x-band prototype) with metallization on both sides. The top metallization consists of a microstrip feed, a broad-band microstrip-to-coplanar stripline (CPS) balun previously reported in [10], and two dipole elements, one of which is the driver element fed by the CPS and the second dipole being the parasitic director. The metallization on the bottom plane is a truncated microstrip ground, which serves as the reflector element for the antenna. The parasitic director element on the top plane simultaneously directs the antenna propagation toward the endfire direction, and acts as an impedance-matching parasitic element.

One of the most unique and effective features of this antenna is the use of the truncated ground plane as the reflector element. The driven printed dipole is used to generate a TE_0 surface wave with very little undesired TM_0 content [11], which can contribute to cross polarization. The truncated ground plane acts as an ideal reflector for this TE_0 mode, which is completely cutoff in the grounded dielectric slab region. In fact, the cutoff frequency for this mode is 39 GHz, which is much higher than the operating frequency of the antenna. The dipole elements of the quasi-Yagi antenna are strongly coupled by the TE_0 surface wave, which has the same polarization and direction as the dipole radiation fields.

As with the classic Yagi-Uda antenna, proper design requires careful optimization of the driver, director, and reflector parameters, which include element spacing, length, and width. While it may seem counter-intuitive that a broad-band antenna will require careful optimization, this *is* essential if desirable radiation characteristics are to be maintained across the entire operating bandwidth. Therefore, we define the bandwidth not only in terms of its matched characteristics, but also in terms of radiation characteristics such as cross polarization, front-to-back ratio, and relatively flat gain. It is also found that the choice of substrate is critical for performance of the antenna. The design requires a high-permittivity design with moderate thickness. This is because the fundamental operation of the antenna relies on surface-wave effects, which are strongly a function of the chosen substrate. Through trial and error it has been found that dielectric with a permittivity of 10.2 and thickness of 0.635 mm is almost ideal for X-band operation. When scaling the antenna to other frequency bands, it is necessary to scale the thickness of the antenna accordingly.

The antenna's dimensions are (unit: millimeter): $W_1 = W_3 = W_4 = W_5 = W_{\mathrm{dri}} = W_{\mathrm{dir}} = 0.6$, $W_2 = 1.2$, $W_6 = S_5 = S_6 = 0.3$, $L_1 = 3.3$, $L_2 = L_5 = 1.5$, $L_3 = 4.8$, $L_4 = 1.8$, $S_{\mathrm{ref}} = 3.9$, $S_{\mathrm{dir}} = 3$, $S_{\mathrm{sub}} = 1.5$, $L_{\mathrm{dri}} = 8.7$, and $L_{\mathrm{dir}} = 3.3$. In this optimized quasi-Yagi design, the length of the antenna's director element is shorter than the conventional Yagi–Uda antenna design and contributes to the broad-band characteristics of the antenna. The total area of the substrate is approximately $\lambda_0/2$ by $\lambda_0/2$ at the center frequency. A photograph of the X-band quasi-Yagi antenna is shown in Fig. 2.

In practice, we have found that the bandwidth of the microstrip–CPS transition does not limit the frequency response of the antenna. This is explored by looking at the response of

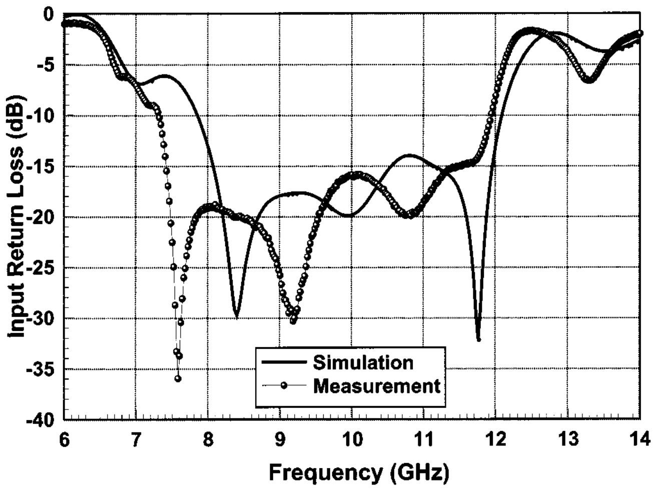


Fig. 3. FDTD simulation and measured input return-loss characteristic of the prototype quasi-Yagi antenna.

the antenna for both microstrip–CPS feeding and with ideal excitation of the antenna. In both cases, the bandwidth of the antenna is quite similar and varies by $\pm 5\%$, depending on the design. Moreover, microstrip–CPS feeding is an extremely practical way of achieving excitation of the antenna while maintaining a high degree of compatibility with other types of components such as amplifiers or phase shifters.

By choosing the antenna parameters properly, the quasi-Yagi antenna demonstrates broad-band (40%–50% for VSWR < 2) characteristics with modest gains ($\sim$4 dBi) or narrower bandwidth (10%–20% for VSWR < 2) with higher gains ($\sim$6.5 dBi). The current design features one director element. Incorporating additional elements has the potential for increasing gain or bandwidth. However, this also increases the number of design parameters as well as the complexity of design optimization, and has not been investigated extensively. The finite-difference time-domain (FDTD) simulation and measured results of the return loss of the broad-band version of the antenna are shown in Fig. 3. The simulated and measured bandwidths are exceptionally wide for such a compact design and are 43% and 48%, respectively (VSWR < 2). All data presented in this paper is based on this design.

Fig. 4 shows the simulated E- and H-plane radiation patterns of both the co-polarization and cross polarization at 9.5 GHz. The figure indicates well-defined endfire radiation patterns with a front-to-back ratio of -16 dB and the maximum cross-polarization level of -18 dB. Further simulations reveal the radiation pattern is quite stable as the frequency changes, with the front-to-back ratio $>$15 dB and cross polarization level < -12 dB across the entire frequency band between 8–12 GHz. This is contrary to many other broad-band planar antenna designs, where increased bandwidth is usually realized at the expense of degradation in either backside radiation or cross polarization.

The radiation patterns have been measured at three different frequencies: 7.5, 9.5, and 11.3 GHz, approximately corresponding to the lower end, center, and upper end frequencies of the operating band of the antenna. The front–back ratio is better than 12 dB and the cross polarization is better than -12 dB

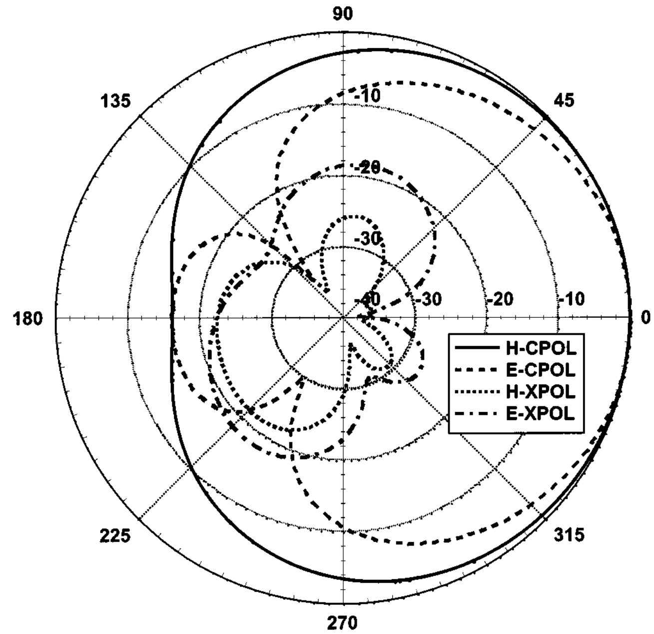


Fig. 4. FDTD simulation results of the E- and H-plane co-polarization and cross-polarization radiation patterns of the antenna at 9.5 GHz.

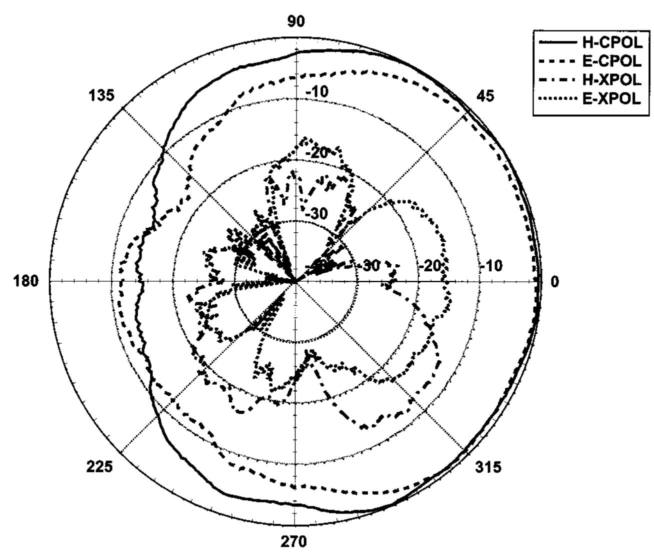


Fig. 5. Measured E- and H-plane co-polarization and cross-polarization radiation patterns of the antenna at 9.5 GHz.

for all frequencies. The measured radiation patterns of the broad-band quasi-Yagi antenna at 9.5 GHz are shown in Fig. 5 and are in close agreement with the simulated patterns shown in Fig. 4. As can be seen, the broad-band quasi-Yagi antenna has a broad single-beam pattern in both the E- and H-plane cuts.

Additionally, the gain of the antenna has been determined both experimentally and through simulation, as shown in Fig. 6. The solid line is the measured result and the dashed line is the simulation result obtained by HP's HFSS. To measure the gain of the antenna, a pair of identical quasi-Yagi antennas is used as both transmit and receive antennas in an anechoic chamber. Once the input and output power of the antenna are measured, the gain is given by the Friis transmission formula [12]. The

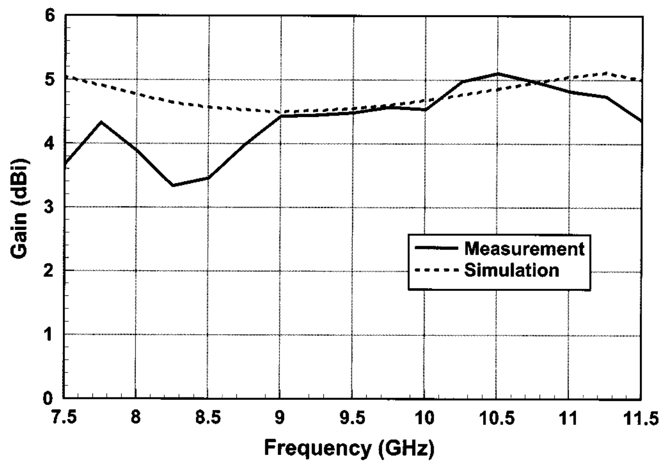


Fig. 6. Simulation and measured results of the antenna's 9-dBi absolute gain.

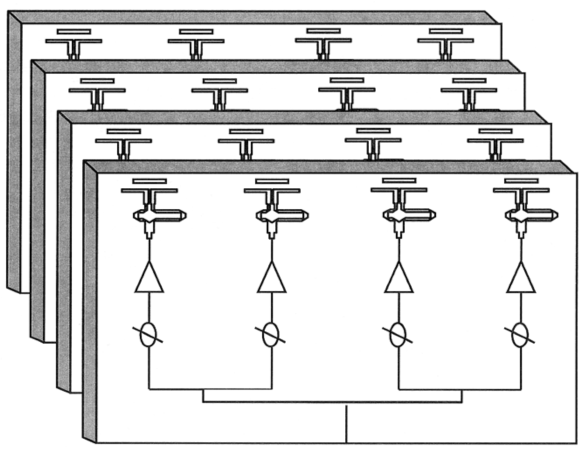


Fig. 7. Proposed card-based architecture of 2-D array using quasi-Yagi antenna.

input return loss and cable losses have been calibrated out of the measurement. However, no attempt was made to calibrate out the connector or microstrip feed losses. From the plot, the measured gain varies from 3.4 to 5.1 dBi, while the simulated gain varies from 4.5 to 5.1 dBi for the entire passband. In general, fair agreement is observed. Additionally, the variation in gain is relatively small across the wide operating bandwidth of the antenna.

III. Planar Quasi-Yagi Antenna Arrays

As an endfire radiator with excellent radiation properties, including broad-band performance, broad-element pattern, and excellent efficiency, the quasi-Yagi antenna can be easily configured into a two-dimensional (2-D) array by simply stacking multiple cards of sub-arrays. This will form a sharp main beam useful for adaptive arrays for communications, spatial power combining or phased array radar, or millimeter-wave imaging [13]. This conceptual architecture is shown in Fig. 7. Due to the linear design of each card, minimal difficulties with signal routing will occur. Additionally, since the antenna is completely compatible with microstrip circuitry, components such as amplifiers and phase shifters can be easily incorporated into each card. Heat dissipation, often a problem in large planar 2-D arrays, can also be addressed by adding additional heat sinking to the microstrip ground plane. The stacked card array also readily allows air cooling or routing for liquid coolant. For these reasons, we believe that the quasi-Yagi antenna will prove to be a valuable array antenna.

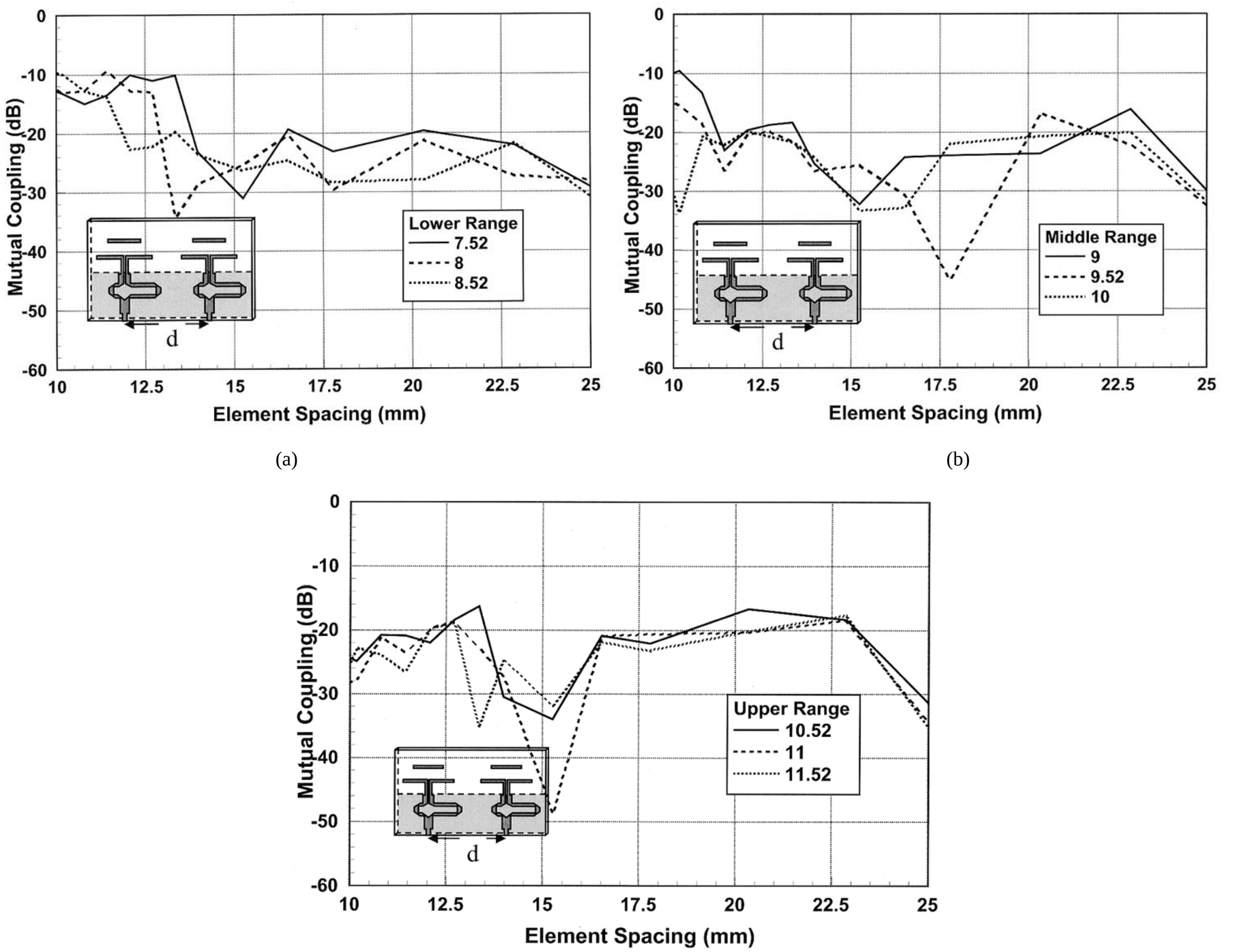
In this section, we explore the quasi-Yagi antenna in an array environment. First, mutual coupling, a crucial factor in array antennas, is explored. Two passive quasi-Yagi arrays are then presented. The first array has an endfire pattern and should be useful as a building block in larger 2-D arrays. The second array uses delay lines to realize a progressive phase shift. The result is a tilted fanbeam pattern with possible applications as a basestation antenna. In the final section, an active eight-element array is presented.

A. Mutual-Coupling Characteristics

One important parameter in this context is the mutual coupling between elements within an array environment, which may not only complicate the array design, but also causes the scan-blindness problem in many existing planar antenna arrays [14]. Despite its very compact design, the quasi-Yagi antenna demonstrates relatively low mutual coupling when placed in an array environment, as compared to patch or LTSA antennas with the same array spacing [15], [16], as will be shown. Two types of coupling were measured in this paper. The first case, i.e., horizontal coupling, is the coupling between two adjacent elements on the same substrate. The second case, i.e., vertical coupling, is the coupling between two elements on adjacent cards coupling through the air. The mutual coupling is determined by the measured direct transmission coefficient S_{21} of the arrays.

Horizontal coupling was experimentally determined as a function of array spacing by fabricating 15 antennas, each with a different spacing to its neighbor on a single substrate. Minimum center-to-center spacing was extremely close, i.e., 10 mm. Maximum center-to-center spacing was 25 mm. The results are shown in Fig. 8(a)–(c), where coupling at specific frequencies in the lower, middle, and upper operating bands of the antenna are shown as a function of frequency. From this, we seen that a horizontal center-to-center spacing greater than 15 mm, which corresponds to $\lambda_0/2$ at the center frequency of the antenna, insure that coupling will be below -18 dB and, in most cases, below -20 dB.

Additional efforts were made to identify the source of mutual coupling for the horizontal case. Possible mechanisms include free-space coupling, coupling by surface waves excited by the feed networks of adjacent elements, and surface-wave coupling through the antennas. To test this, four test structures were developed. Each of these consisted of eight quasi-Yagi antennas spaced 15 mm apart. The first structure consisted of standard quasi-Yagi antennas. The second structure tested feed-network coupling by etching a 2-mm gap in the ground plane between adjacent antennas to suppress any surface waves between them. The third structure tested antenna–antenna coupling by voiding a 2-mm gap in the dielectric material after the truncated ground plane, which should disrupt any surface waves propagating in this region. Finally, a fourth test structure was constructed, combining the ground-plane etching of the second



(a) (b) (c)

Fig. 8. Mutual coupling as a function of element spacing d for: (a) lower (b) middle, and (c) upper frequency ranges.

fixture and the dielectric voiding of the third structure. Mutual coupling of the inner two elements was measured with a network analyzer. The remaining six outer elements were terminated with 50-Ω loads to simulate an array environment. It was found that mutual coupling in all four case were virtually identical, with only minor deviations observed. From this, we conclude that, for 15-mm-array spacing, mutual coupling is almost solely due to coupling through the air.

Finally, vertical coupling was experimentally determined. In this case, four cards, each with three elements horizontally spaced by 15 mm, were tested with center-to-center horizontal spacings of 15 and 20 mm. The results are shown in Fig. 9. From this, we see that vertical coupling is somewhat stronger than horizontal coupling for comparable center-to-center spacing. This is due to the broader H-plane pattern of the quasi-Yagi element. Maximum coupling for 15-mm spacing is -17.5 dB at 8.5 GHz and -16.5 dB at 10 GHz for the 20-mm case. However, the mutual coupling is below -20 dB for two-thirds of the bandwidth shown in Fig. 9 for both cases.

B. Passive Quasi-Yagi Arrays

A simple equal-amplitude eight-element linear array is used to demonstrate the viability of the quasi-Yagi as an array

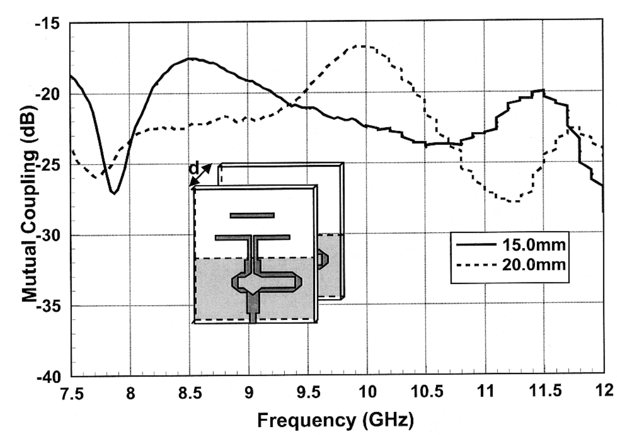


Fig. 9. Vertical mutual coupling as a function of frequency for 15- and 20-mm spacing.

antenna. Two arrays are built, the first with the main beam at endfire direction of the quasi-Yagi elements, and the second uses microstrip delay lines so that the main beam is tilted to approximately 12° from endfire. Each array has a fanbeam pattern, which makes it applicable to mobile communications.

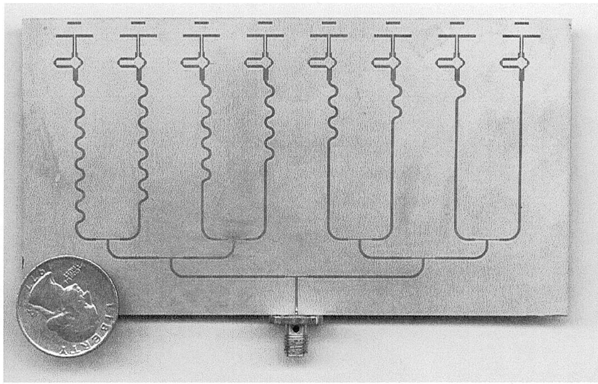


Fig. 10. Photograph of eight-element quasi-Yagi with delay lines for tilted fanbeam radiation pattern.

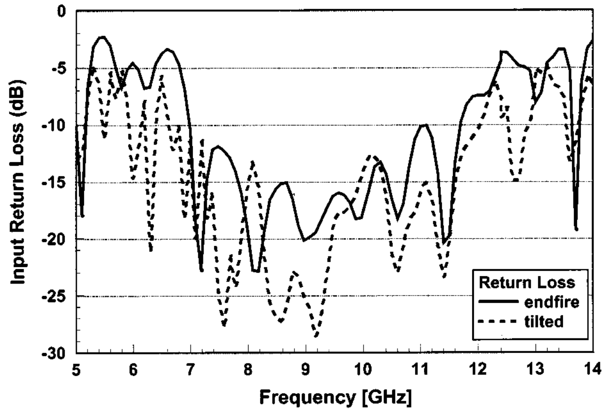


Fig. 11. Measured return loss for endfire and tilted fanbeam quasi-Yagi arrays.

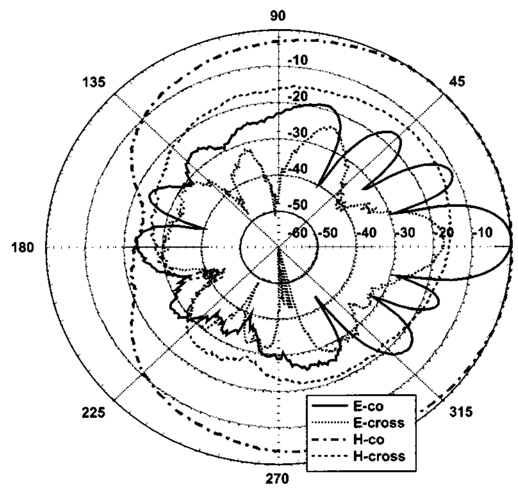


Fig. 12. Radiation properties of eight-element endfire quasi-Yagi array.

However, we believe that the single-substrate design can be integrated into large 2-D arrays for radar, communications, and quasi-optical power-combining applications. We believe this card-based scheme should be an extremely cost-effective solution to alleviate routing and heat-sinking problems associated with typical 2-D arrays. The low mutual coupling between adjacent quasi-Yagi elements and the narrow physical width of the antenna gives great flexibility in array spacing not available with other endfire antennas, such as the Vivaldi, which are typically much wider.

Each array is fabricated on a single piece of RT/Duroid with $\varepsilon_r = 10.2$ and a substrate thickness of 0.635 mm. A photograph of the tilted beam array is shown in Fig. 10. The width of each board is approximately 13.5 cm. The only difference between the two arrays is the inclusion of microstrip delay lines on the tilted beam array to realize a progressive phase delay between elements and, hence, a beam tilted away from the endfire direction. Each array utilizes a simple corporate feed with binary dividers composed of T-junctions and quarter-wave transformers. The overall insertion loss, including connector loss, has been measured to be about -1 dB for the array without the additional microstrip delay lines of the tilted array. This was measured by constructing two 1-8 dividers back-to-back and taking half the total insertion loss. The measured S-parameters of each array are shown in Fig. 11. In both cases, the bandwidth (VSWR < 2) is approximately the same as the bandwidth of the quasi-Yagi element, i.e., about 50%.

The radiation patterns of each antenna has been measured across the operating bandwidth in an anechoic chamber. Radiation patterns for the endfire array at 9 GHz is shown in Fig. 12. For this particular frequency, the front-to-back ratio of the endfire array was found to be better than 20 dB. Additionally, the cross polarization in the main beam is better than -15 dB. One of the first sidelobes is slightly higher than the expected -13.5 dB for this type of array, i.e., about -12 dB. The other first sidelobe is slightly lower than expected, i.e., -15.5 dB. This discrepancy is due to either small error in the feed network or measurement error in the anechoic chamber.

The radiation patterns of the tilted beam array were also measured. The E-plane of the tilted beam antenna is shown in Fig. 13 at 8, 10, and 11.7 GHz. The measured 3-dB beamwidth ranges from 10° to 17° in this frequency range. Additionally, the sidelobe levels range from -11 to -14 dB. This may be improved using a more sophisticated beamforming technique such as the Chebyshev distribution rather than the simple equal-amplitude distribution used with this proof-of-concept array at the cost of increased beamwidth.

C. *Active Quasi-Yagi Array*

Active arrays or arrays with amplifiers incorporated directly at the antenna platform have received a good deal of attention in recent years. In the case of a transmit array, the power amplifier (PA) is placed directly at the antenna to avoid the losses associated with the feed network or other components (such as phase shifters). The increase in system efficiency can be dramatic, thus allowing smaller and lighter heat sinking and batteries. Low-noise amplifiers (LNA's) can be incorporated directly at the antenna platform of a receive array for increased sensitivity. In this section, amplifiers are incorporated into the linear eight-element array to form an active transmit array.

The completed array is shown in Fig. 14. For simplicity, matched GaAs FET gain block amplifiers are used as the active device. By placing the amplifiers directly at the antenna, the combining losses are essentially limited to that of the quasi-Yagi. Input return loss of the completed active array is

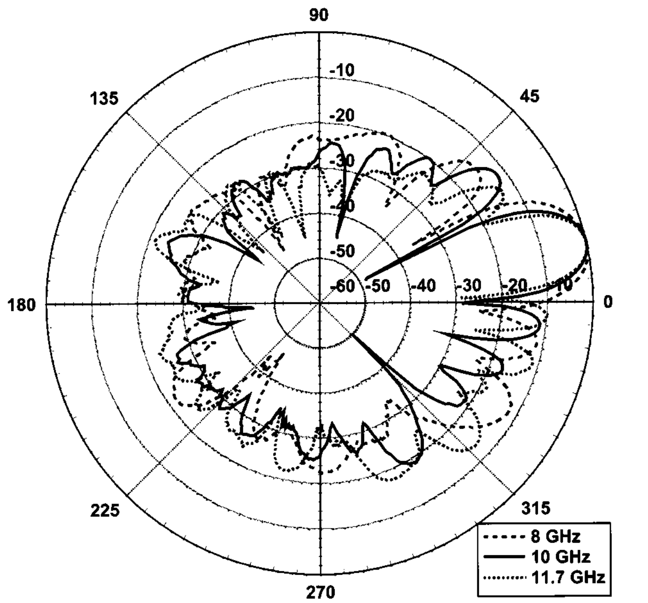


Fig. 13. E-plane of tilted fanbeam quasi-Yagi array at different operating frequencies.

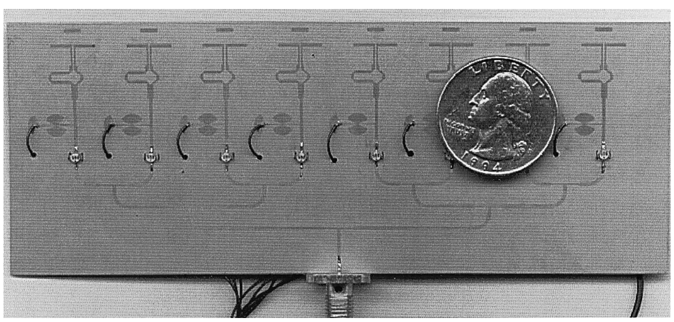


Fig. 14. Photograph of eight-element active quasi-Yagi array.

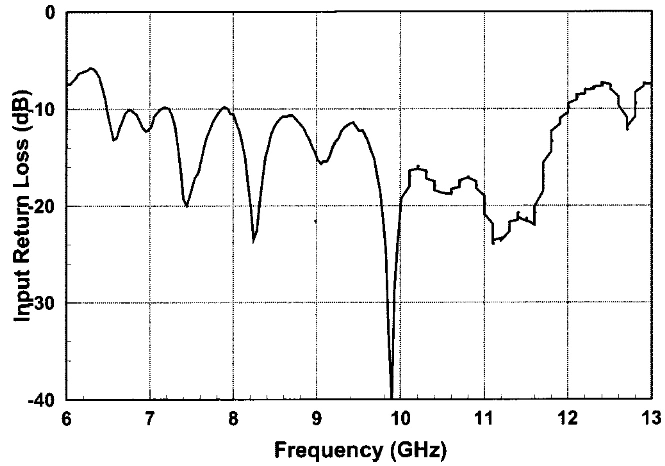


Fig. 15. Return loss of eight-element active quasi-Yagi array.

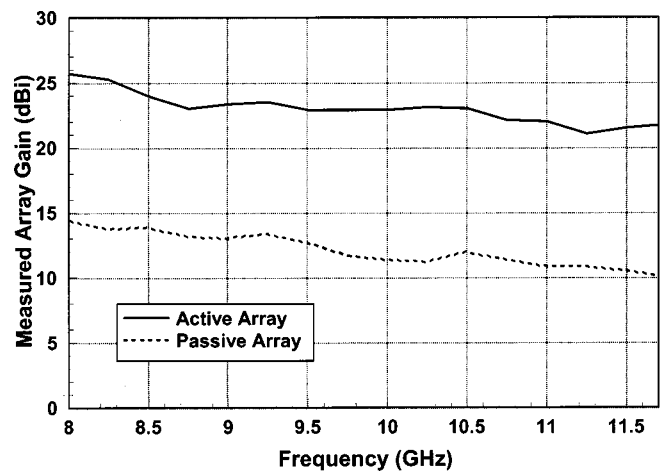


Fig. 16. Measured gain of active and passive endfire quais-Yagi arrays.

shown in Fig. 15. Due to the internal matching of the GaAs FET amplifiers, the bandwidth of the active array is larger than that of the passive eight-element array (VSWR < 2), and is 60%, quite large for a planar active antenna array. However, the increased bandwidth is added at the lower frequency end where the quasi-Yagi's cross-polarization and front-to-back ratio deteriorates. Therefore, the increased input match probably does not translate into increased usable bandwidth in this case. The radiation patterns were measured in the operating range of the quasi-Yagi antenna and were seen to be virtually identical to those of the passive array, as shown in Fig. 12.

Finally, the gain of the passive and active arrays has been measured from 8 to 11.7 GHz, and is shown in Fig. 16. The gain was measured using the gain substitution method with a standard gain horn. The difference in the gain between the two plots corresponds to the gain of the amplifier. The gain changes by about 3 dB in this bandwidth. Average gain is about 12 dBi for the passive array and 23 dBi for the active array. The gain is also very close to its expected value, which can be computed by knowing the gain of the array factor, the element gain (shown in Fig. 6), and approximately the losses of the feed network, which were determined to be about -1 dB, including connector loss. The discrepancy between expected gain and measured gain is 0.6 dB at 9 GHz, 0.3 dB at 9.5 GHz, and 0.5 dB at 10 GHz. This low figure gives credence to both the design and measurement procedure.

IV. Conclusion

In this paper, a very compact and simple planar antenna based on a modification of the classic Yagi–Uda antenna has been presented, as well as several arrays using this antenna as a radiating element. The antenna achieves extremely wide frequency bandwidth and good radiation characteristics in terms of beam pattern, front-to-back ratio, cross polarization, and low mutual coupling. The antenna experimentally demonstrated a bandwidth of 48% for the VSWR < 2, better than 12-dB front-to-back ratio, and gain between 3–5 dBi. Additionally, mutual coupling has been measured. Horizontal coupling of antennas on the same substrate was found to be below -18 dB for center-to-center spacing greater than 15 mm ($\lambda_0/2$ at the center frequency) and better than -20 dB for most frequencies. Additionally, investigations reveal that horizontal mutual coupling is almost solely due to air coupling. Vertical coupling was found to be somewhat stronger than horizontal coupling, due to the broader H-plane pattern of the antenna and reached a peak value of -17.5 dB for a vertical spacing of 15 mm and −16.5 dB for a vertical spacing of 20 mm.

The excellent radiation properties and compact size of this antenna make it ideal as either a standalone antenna with a broad pattern or as an array element. We have presented three simple arrays using the quasi-Yagi antenna. All three eight-element arrays are fabricated on a single card, which can be used as a building block of a larger 2-D array or standalone as a basestation antenna with a fanbeam radiation pattern. We are currently working to incorporate the single card linear arrays into a larger 2-D array.

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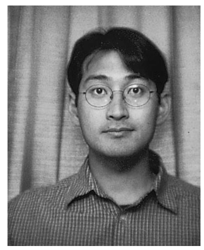

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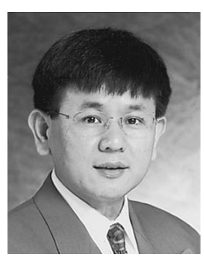

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