Title: Compact and Broadband Quasi-Yagi Antenna for X- to Ku-band Applications

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Compact and Broadband Quasi-Yagi Antenna for X- to Ku-band Applications

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Abstract

A compact, broadband quasi-Yagi antenna utilizing an ultra-wideband microstrip-to-coplanar stripline (MS-to-CPS) balun is proposed. Excellent broadband phase and amplitude balance is possible due to the ultra-wideband MS-to-CPS balun based on field and impedance matching concept. The implemented antenna provides very wide bandwidth from 7 to 15.1 GHz (73.3%). The gain of the antenna is from 3.7 to 5.5 dBi, the front-to-back ratio is more than 10 dB, and the nominal radiation efficiency is about 94%. The antenna design can be scaled up to mm-wave frequencies.

1. Introduction

Simple planar quasi-Yagi antennas [1] have widely been used in microwave/mm-wave wireless systems because of their broad bandwidth, good gain, low cost, simple fabrication, and ease of integration with microwave integrated circuits (MICs). Several types of design for the planar quasi-Yagi antennas have been reported for various applications such as phased arrays, power combining, and active arrays [1]–[7]. The driver dipole element was used mainly to excite the TE-mode surface wave. The truncated microstrip ground plane acted as a reflecting element for the surface wave, resulting in forward-directed radiation. With these antennas, the designs of the antenna radiating parts were similar, but the main differences lied at the antenna feeding networks.

The antenna feeding structures are balun structures to transform the transmission line mode at the antenna input to the coplanar stripline (CPS). Examples of various feeding structures used for the quasi-Yagi antennas are MS-to-CPS balun (or transition) in [1][2], coplanar waveguide (CPW)-to- CPS balun in [3][4], MS-to-slotline balun in [5], and the broadside coupled MS-to-CPS balun in [6][7].

The complexity of feeding structures often increases design factors and thus optimization time, but also intrinsically limits the frequency bandwidth of the driven element. In order to obtain the required bandwidth and gain from the antenna, with an EM simulator, a significant amount of simulation time would be required to tune and optimize the antenna parameters.
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including balun and transformer for impedance matching. In many of the reported design approaches, there were no explicit guidelines suggested for performing impedance matching between the CPS line and the input microstrip transmission lines [1], [3]–[7]. In addition, in the design of most commonly used MS-to-CPS balun structures for the quasi-Yagi antenna suggested by [7][8], 180 degree phase difference on the CPS lines was guaranteed only for narrow bandwidth near the center frequency; i.e., the odd-mode conversion with the phase delayed leg was expected to work only for narrow frequency bandwidth. Also, most of the broadband quasi-Yagi antenna designs were mainly based on return loss performances. Broad impedance bandwidth, of course, is a necessary requirement for the broadband antennas, but may not be a sufficient criterion for good radiation characteristics for whole frequency band. Moreover, amplitude and phase imbalances on the CPS feed lines were not investigated in previous designs of broadband quasi-Yagi antennas [1]–[7].

A systematic design approach of broadband quasi-Yagi antennas utilizing ultra-wideband MS-to-CPS balun [9] was introduced by the author’s group [2]. Due to the ultra-wide bandwidth and good balance of the balun, the antenna design process was simple impedance matching between the balun and antenna radiating components. With that design, however, a metal strip used for a reflector was located at the bottom layer of the antenna. At mm-wave frequencies, EM interaction levels between the reflector strip on bottom layer and the CPS feed line on top layer might not be negligible, and therefore, the front-to-back (F/B) ratio and backside radiation patterns were sometimes degraded. The antenna size was also relatively larger than other configurations of the quasi-Yagi antennas.

In this paper, a modified compact, broadband planar quasi-Yagi antenna using the ultra-wideband MS-to-CPS balun with improved performance is presented. A reflector strip on bottom layer under the CPS line is replaced by the shaped bottom ground plane, which reduces the antenna size and backside radiation. The antenna design can be easily scaled for broad range of operating frequencies up to mm-wave frequencies. Also, the effects of amplitude and phase imbalance of the MS-to-CPS balun over the operating frequency band are discussed.

2. Balun and Antenna Design

Figure 1 shows the configuration of the proposed quasi-Yagi antenna using the ultra-wideband MS-to-CPS balun. The antenna consists of the antenna feeding structure and the quasi-Yagi radiating elements. The antenna feed structure is composed of a microstrip line and the ultra-wideband MS-to-CPS balun. The radiating parts of the antenna consist of one dipole antenna (driver) and a conductor strip (parasitic director). The bottom ground conductor layer is shaped to serve as a reflector for the antenna. For design of the balun [15], the field distribution of the microstrip line is gradually transformed to that of the CPS through the ground-shaped structure
while providing the ground continuity by using several via holes to maintain the same ground potential for broad bandwidth. In order to optimally match the characteristic impedances between the microstrip line and the CPS, for a given taper length, the Klopfenstein impedance taper has been used to minimize the reflection coefficient over the operating bandwidth. The balun has proven to provide broadband amplitude and phase balances between two CPS strips.

![Figure 1. Configurations of the proposed quasi-Yagi antenna. Antenna design parameters (in unit of mil):](image)

$L_1=245, L_2=310, W_1=70, W_2=60, S_d=35, S_r=225, S_g=5, L_{cps}=50, W_{cps}=30$ and $L_{bal}=260$.

The proposed antenna was designed by the following procedure. Firstly, an ultra-wideband MS-to-CPS balun was designed using the guidelines presented in [15] as shown in Fig. 1. The substrate used in this design was the Rogers RO4003® ($\varepsilon_r=3.38, \tan\delta=0.0027$) substrate with 20-mil thickness. The characteristic impedance of the CPS is usually higher than that of the microstrip line within typical substrate fabrication limits. The characteristic impedance of the CPS was chosen as about 107 $\Omega$ with 5 mil gap ($S_g$) between CPS strips and 30 mil strip width ($W_{cps}$). Secondly, the quasi-Yagi radiating elements (driver and parasitic director) were optimized to achieve a wide impedance bandwidth and good radiation performance over the broad frequency bandwidth from X- to Ku-band. The driver length ($L_2$) was chosen to about $\lambda_0/4$ at 9 GHz to provide good performance at low-band frequencies. The director length ($L_1$) and spacing ($S_d$) were optimized for performances at high-band frequencies. The spacing ($S_r$) between the dipole and the bottom ground conductor was about $\lambda_0/4$ at 12 GHz to reduce backward spill-over.

After optimization and implementation, the size of the antenna was approximately 19 mm × 20 mm (0.63 $\lambda_0 \times 0.67 \lambda_0$), where $\lambda_0$ is the free space wavelength at the center frequency. The area
of the proposed antenna takes only 53% of our previous design [2]. If the antenna is to be designed with a high-permittivity substrate, the antenna size can be further reduced.

3. Experimental Results

Firstly, to evaluate performance of the balun, a back-to-back configuration of the balun was designed and implemented with the CPS length of 210 mil and the balun length (Lbal) of 260 mil. 3-D EM simulations were performed with the ANSYS® HFSS™. It is can be seen from Fig. 2 that measured insertion loss is less than 1 dB per balun from 7 to 20 GHz. The simulated and measured results of the balun indicate that the impedance bandwidth with more than 10 dB return loss is from 7 to over 20 GHz. As can be seen, simulated results agree closely with measured results.

![Back-to-back configuration of the MS-to-CPS balun](image)

Figure 2. Back-to-back configuration of the MS-to-CPS balun
To maintain close to 180 degree phase difference between the CPS strips, a balun must be properly matched and properly excite the odd mode on the CPS strips. Poor excitation of the odd mode on the CPS line can cause degradation of the radiation patterns. EM simulation studies have been performed to evaluate phase and amplitude imbalances at the CPS port. Similarly to the test method suggested by [16], which used the CPS line symmetrically split into two CPW ports, the balanced CPS line was symmetrically split into two unbalanced MS output ports. The bottom layer of each output MS port was tapered for good impedance matching. For 6 to 16 GHz range, the amplitude difference between the two CPS strips (S21 and S31) was less than 1 dB as shown in Fig. 3.
In [16], an amplitude imbalance less than 1.5 dB for entire bandwidth was suggested to be adequate for broadband antennas. Also, with the proposed balun, the phase deviation from 180° between the two CPS strips was maintained within 7° (from 178° to 185°) over whole operating frequencies. The maximum allowable phase imbalance may be dependent on specific applications, but, in general, ±5° deviation from 180° is considered as a criterion of well-designed balun [16]. Therefore, the proposed MS-to-CPS balun is considered to be quite suitable for broadband quasi-Yagi antenna and other balanced antennas (e.g., tapered slot antenna) [17].
The designed and fabricated quasi-Yagi antenna is shown in Fig. 4. In the picture, the top ground conductor planes were added for installation of an RF connector for measurements, and these did not change the performance of the balun. Figure 5 shows comparisons of the measured and simulated return losses of the antenna elements: i.e., the 2-element dipole array (A), the dipole array and reflector without balun (B), and the whole antenna (C). The measurement was carried out by using an Anritsu universal test fixture 38801K, which allowed the maximum usable frequency up to 40 GHz. As can be seen in Fig. 5, the bandwidths of the antenna elements are almost same. The addition of the reflector and balun to the two dipole array did not change the bandwidth of the dipole array, thus simplifying the antenna design process. Figure 6 shows the simulated and measured VSWR. The measured VSWR agrees closely with the simulated one. The antenna operates from 7 to 15.1 GHz covering the X- to Ku-band. The antenna bandwidth with 10 dB return loss is approximately 73.3%.

![Simulated and measured VSWR](image)

**Figure 6.** Simulated and measured VSWR

Figure 7 shows the simulated and measured antenna gain and radiation efficiency. The antenna gain varies from 3.7 to 5.5 dBi within the antenna bandwidth of 10 dB return loss. Some discrepancies noticed between the simulated and measured antenna gain may have been caused by fabrication and measurement tolerances. Also, relatively low antenna gain between 11 GHz to 13 GHz may have been caused by return loss degradations due to mismatch loss of broadband design. There is a trade-off between antenna gain and bandwidth. The simulated radiation efficiency of the antenna is nominally 94% for the operating frequencies.
The current density distributions at 8 GHz and 14 GHz on the surface of the antenna were analyzed using CST microwave studio® as shown in Fig 8. As can be seen, at low-band frequencies (8 GHz), driver dipole was mainly used to excite the surface wave. The driver dipole determines the antenna’s low-band characteristics. On the other hand, at high-band frequencies (14 GHz), the director works as a parasitic element, generating mutual coupling with driver dipole. Hence, director length \( L_1 \) and distance from driver \( S_d \) are important parameters on improving the high-band performances.

Figures 9 (a)-(d) show the measured normalized radiation patterns at 8, 10, 12, and 14 GHz, respectively. As can be seen, the measured radiation patterns are very similar and uniform over
the whole operating frequencies. The half-power bandwidth (HPBW) of E-plane is typically about 80°. The front-to-back (F/B) ratio is the ratio of the maximum forward directivity to that of the backward direction. Measured F/B ratio ranges from 10 to 25 dB. The measured cross-polarization levels are better than -10 dB. The performances of the proposed quasi-Yagi antenna are summarized and compared with the reported antennas in Table 1. As can be seen, the proposed antenna exhibits much wider bandwidth, smaller size, and good radiation performances as compared with the previous designs [1–13]. In order to obtain higher antenna gain, the antenna dimension of the radiating parts can be adjusted. Another way to increase antenna gain is by adding additional directors along end-fire direction. For both cases, the frequency bandwidth may be traded-off. A simulation study indicates that the antenna with two directors increases approximately 1 dB of gain in comparison with single director case. A simulation study indicates that the antenna with two directors increases approximately 1 dB of gain in comparison with single director case. More design parameters, however, increase design complexity.
Figure 9. Measured normalized radiation patterns: (a) 8 GHz, (b) 10 GHz, (c) 12 GHz, and (d) 14 GHz.
(CO-POL: co-polarization, X-POL: cross-polarization)

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<th>Table 1. Performance summary of the quasi-Yagi Antennas</th>
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4. Conclusion

In this paper, a compact, broadband quasi-Yagi antenna utilizing ultra-wideband MS-to-CPS balun has been introduced. The shaped bottom ground plane serves as a reflector and helps to reduce the antenna size by 53% of the previous design. It also helps to reduce EM interactions between the reflector and the CPS feed; thereby, the design is scalable to mm-wave frequencies. The MS-to-CPS balun provides excellent phase and amplitude balances for the operating bandwidth. The measured radiation patterns show very similar performances for the whole operating frequency band. The proposed antenna can be a cost-effective solution for various compact, broadband phased arrays and imaging systems for microwave/mm-wave frequencies.

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Reference

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