Tapered microstrip balun for integrating a low noise amplifier with a nonplanar log periodic antenna

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This article describes design parameters and test results for a 1–10 GHz microstrip balun with a 240 Ω balanced port and a 50 Ω unbalanced port. The tapered geometry and rf performance are favorable for integrating a low noise amplifier with a nonplanar log periodic antenna developed at the University of California's radio astronomy lab. The design can be modified for use in cryogenic low noise applications. When the balun is placed in a conducting enclosure, excitation of unwanted transmission modes can be minimized by careful field and impedance matching of balun ports and by inclusion of a resistive vane in proximity to the balun.
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INTRODUCTION

Two nonplanar log-periodic (LP) antennas can be combined to produce rf feed with dual polarization and low cross polarization coupling. The resulting four-arm antenna has a pyramidal shape, which can couple to orthogonal modes of linear polarization. The main radiation lobe is circular down to the −15 dB power contour, with maximum gain in the direction of the antenna apex. We fabricated such an antenna with a 20° opening angle between opposite arms, achieving a forward gain of 12 dB and cross polarization coupling of ∼−25 dB.[1,2] Fixed between the arms of this antenna is a grounded pyramidal metallic shield with a 10° opening angle, which provides an isolated space for two low noise amplifiers (LNAs), one per polarization channel. For improved noise performance, this shield may also house a compact cryogenic refrigerator to cool the amplifiers.

Connecting the balanced leads of this antenna to an unbalanced coaxial LNA module (or transmission line) requires a broadband balun which matches the 240 Ω terminal impedance of the antenna to the 50 Ω amplifier input and which can be threaded through the narrow geometry of the shield near the antenna terminals. A design for such a balun is presented in this note.

BASIC DESIGN AND MODELING

Simply stated, a balun is a reciprocal transducer, converting the odd signal mode at the antenna terminals to the sum of an odd and even mode at the terminals of an unbalanced (grounded) transmission line structure.[3] In effect, it passes microwave energy while blocking net rf current flow between the two ports. Space constraints in a narrow pyramidal shield and the need for wide bandwidth make a tapered microstrip design ideal. Gans *et al.*[4] demonstrated an example of a tapered microstrip balun. This is an evolvement of an early broadband balun realized in coaxial line by Duncan and Minerva.[5]

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Figure 1 shows the balun we designed, and Fig. 2 shows the tip of the dual polarization feed structure with the baluns connected—the inset shows more of the feed for visual reference. To achieve good performance at 10 GHz, the log periodic antenna must be truncated at the high frequency end by no more than 0.850 in. below the vanishing point of the self-similar antenna structure continued to arbitrarily high frequency. At this displacement, the opening of the pyramidal shield is 0.150 in.×0.150 in. and the antenna terminals are separated by 0.300 in. Moreover, since the antenna has two polarization channels, the twin-lead ports of the baluns must be brought through the narrow end of the shield without inducing significant cross-polarization coupling. For this reason, the shield volume is partitioned by a metallic septum, so that the baluns do not capacitively couple.

The shield volume is partitioned diagonally so that the balanced port of each balun can be located to give maximum separation from the surrounding grounded metal walls, which limits the highest practical impedance one can achieve with a twin-lead printed on commercial PC board. The balanced port of each balun must have the same impedance as the antenna terminals (240 Ω). This can be conveniently achieved within the available space constraints by fabricating offset 0.010 in. microstrip lines separated by 0.050 in. on opposite sides of 0.015 in. thick Cuflon. The balun leads are approximately 0.050 in. equidistant from the septum and pyramidal shield walls. Cuflon[6] was chosen over Duroid 5880[7] circuit board material because the combined ohmic and dielectric losses are nearly a third less over the band.

The twin-lead input of the balun is a 240/50 Ω impedance transformer. The input of the balun transducer section, described in the next paragraph, is a broadside-coupled pair of 0.060 in. lines. For reasons of space economy it is most conveniently mated to the twin lead input by asymmetrically tapering top and bottom conductors [Fig. 3(a)] so that the outer diameter of the pair remain constant (0.060 in.). The cross section of the balun is shown in Fig. 1 as the lower set of figures. Simulation with IE3D[8] gives the impedance of this transmission line structure as a function of a single linear

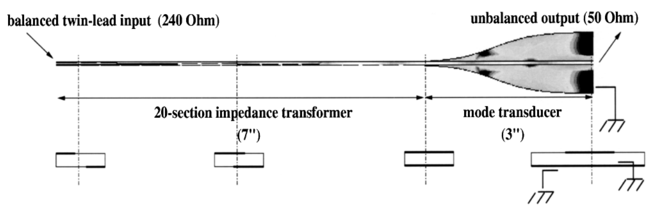

FIG. 1. Drawing of the balun: (Bottom) the cross section at different places along the line.

parameter X [see Figs. 3(a) and 4]. Figure 4 also shows the impedance along the line (Z). The impedance steps yield a 20-section 240/50 Ω transformer of minimum length with a −25 dB return loss (Klopfenstein taper).[9] The number of sections limits the high frequency limit (>10 GHz), and the total length determines the low frequency cutoff (<1 GHz). Full wave simulations predict a return loss of less than −25 dB and an insertion loss of 0.2–0.4 dB [Fig. 3(b)].

The transducer section [Fig. 5(a)] consists of a 0.060 in. wide line broadside coupled through the substrate to a line of the same width at the balanced port which flares out quasiexponentially. At the unbalanced port, the balun transducer is effectively a microstrip line, where the bottom conductor becomes a ground plane (it is attached to case ground along the end). The length of the transducer and speed of the taper of the bottom conductor line determine the passband of the transducer section, which has been optimized for 1–10 GHz. Full wave simulations predict a return loss of ∼−20 dB and an insertion loss of less than −0.2–−0.3 dB [Fig. 5(b)].

TEST RESULTS

As shown in Fig. 1, this taper-line balun has two sections: the balanced line portion which matches the antenna impedance to ∼50 Ω and a portion which actually performs the mode transduction. One method to confirm the proper function of this balun design is to connect two baluns end-to-end at their balanced ports. This requires fabricating a balun similar to the first but with the conducting features reflected about the midline. S-parameter measurements can then be performed with an Agilent 8722ES network analyzer.

Figure 6 shows that the net insertion loss of this circuit at room temperature is ∼−1 dB for 1–7 GHz and ∼−2 dB for 7–11 GHz. This is somewhat greater than the −0.8–1.4 dB loss predicted by doubling the simulated losses. The discrepancy arises partially from the lack of a correction to the simulation for the effects of dielectric surface roughness. The return loss $|S_{11}|$ is −15–−20 dB across the band.

To check the phase performance of the balun, we made a second circuit configuration by connecting the two baluns end-to-end as before but with the twin leads cross-connected i.e., one of the baluns is flipped 180° about its midline. Since the balun transforms a balanced signal in the H plane to an unbalanced signal in the E plane, a comparison of the two

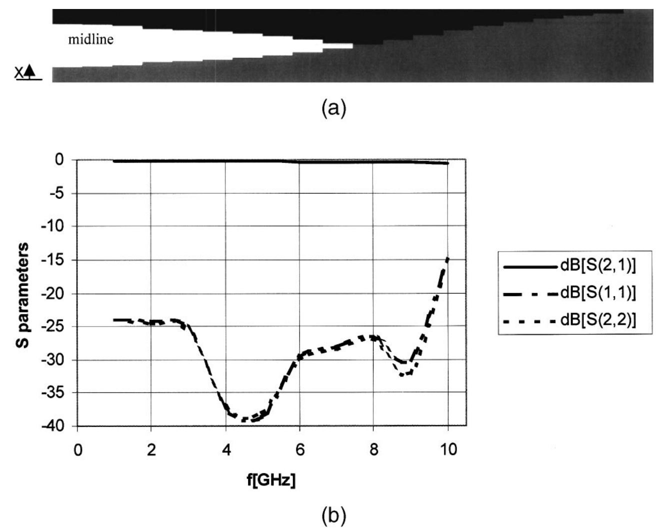

FIG. 3. (a) Matching transformer section of the balun showing the offset X. (b) Full wave simulation of the transformer section of the balun; shown are S_{11}, S_{21}, and S_{22}.

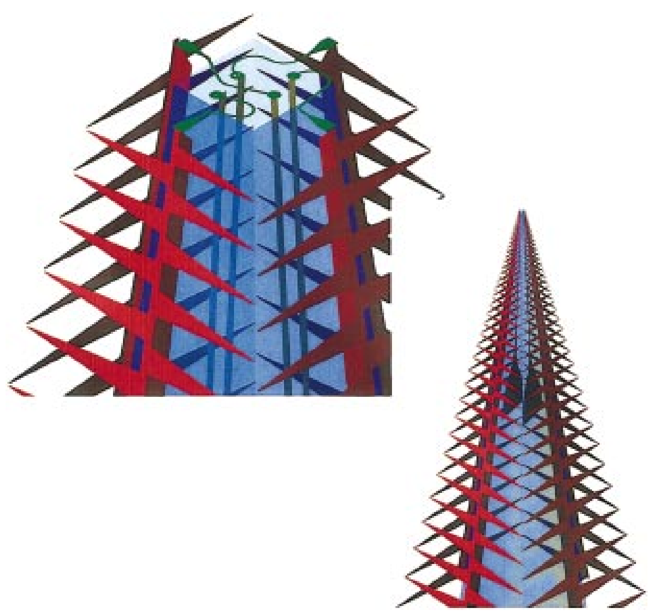

FIG. 2. (Color) Feed with baluns and feeder tip circuit board: (inset) the upper third of the full-size feed. The inner pyramidal shield is translucent.

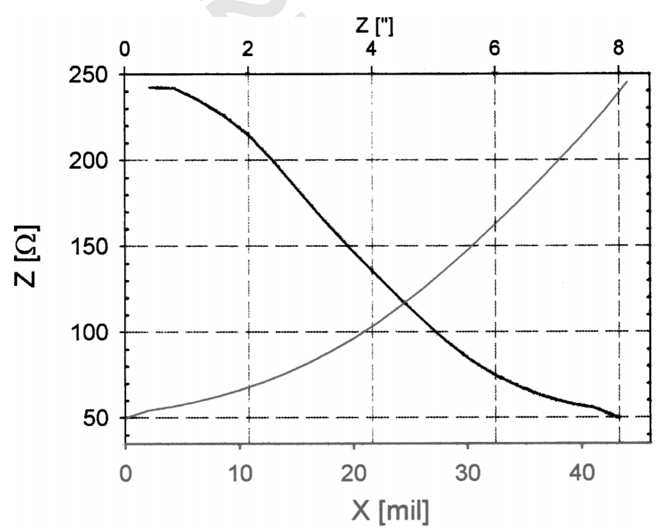

FIG. 4. (Red) Impedance as a function of X, the inner line separation, with the outer line separation of 0.060 in., and Cuflon thickness of 0.015 in. (Black) Impedance along the line Z.

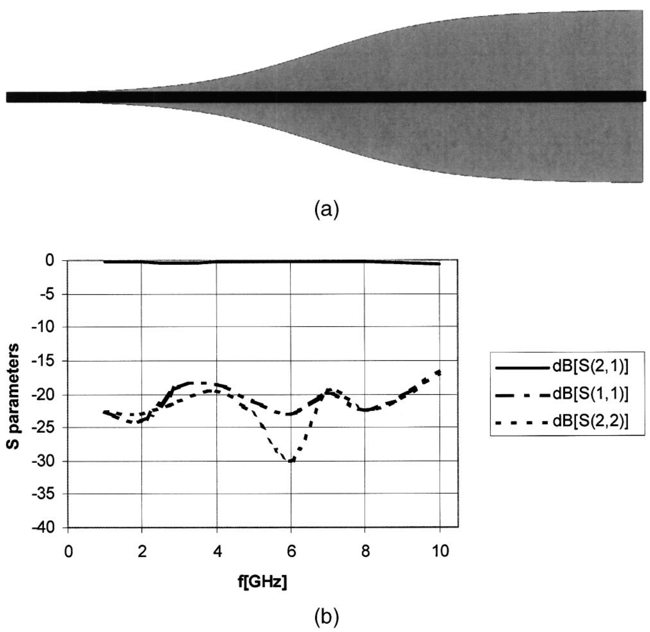

FIG. 5. (a) Transducer section and unbalanced ‘‘microstrip’’ end of the balun. (b) Full wave simulation of the transducer section of the balun. Shown are S_{11}, S_{21}, and S_{22}.

back-to-back balun configurations should exhibit a 180° phase difference. A thru calibration is performed with the network analyzer attached to the first end-to-end balun circuit configuration, after which the phase of the second configuration is measured. Figure 7 shows that from 1 to 10 GHz the measured phase difference between the two back-to-back configurations is 180°±2°.

DISCUSSION

The results quoted in the previous section apply to balun pairs mounted in an open test fixture. For this balun to properly link a LNA with our LP antenna, it must operate in a metal pyramidal shield. The effects of nearby conducting walls are twofold: (1) they lower the characteristic impedance of both balanced and unbalanced transmission lines and (2) they provide a conduction path for in-phase signals (the even mode) along the twin leads. Care must be taken to avoid significant excitation of the even mode, which can raise sidelobe patterns and reduce the forward gain. Simulations show that with good impedance and field match to the balun at both ports (with careful design of the rf transitions) the even mode excitation should be negligible. Indeed, placing our end to end balun test fixture in a long metal box approximately 1 in.×1 in. in cross section increases measured loss by less than 0.05 dB—this seems to indicate minimal coupling to the even mode at the unbalanced ports. Nevertheless, special care must be taken against misalignment of the balun in narrow asymmetric metal enclosures which can lead to the excitation of common modes or to high-Q cavity modes.

One way to attenuate any possible unwanted modes on an enclosed balun is to attach a resistive card vane to the inside of the radiation shield, perpendicular to the plane of the balun along the midline (Fig. 8). Care must be taken not to attenuate the odd mode, particularly in locations where the fringe fields between balanced leads are significant. To avoid this, the vane should probably have maximum extent at the balun ‘‘neck’’ (the transducer input) where balanced lines are broadside coupled and fringe fields are at minimum strength.

Use of a tapered microstrip balun in a narrow cryostat requires scaling the design to quartz (ε=3.8–4.5) or alumina

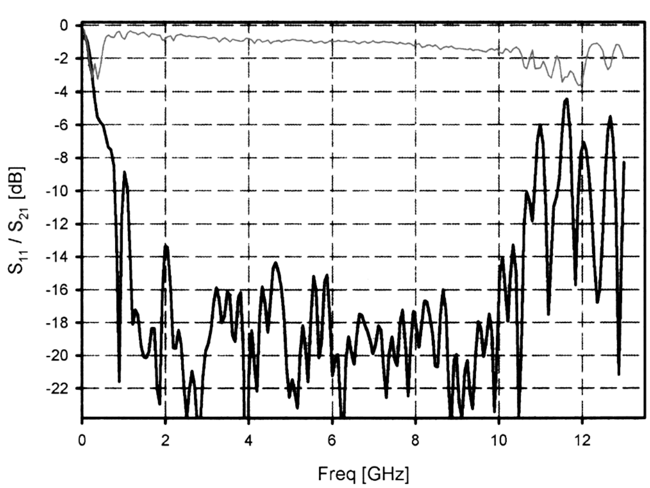

FIG. 6. Measured S parameters of end-to-end balun circuit.

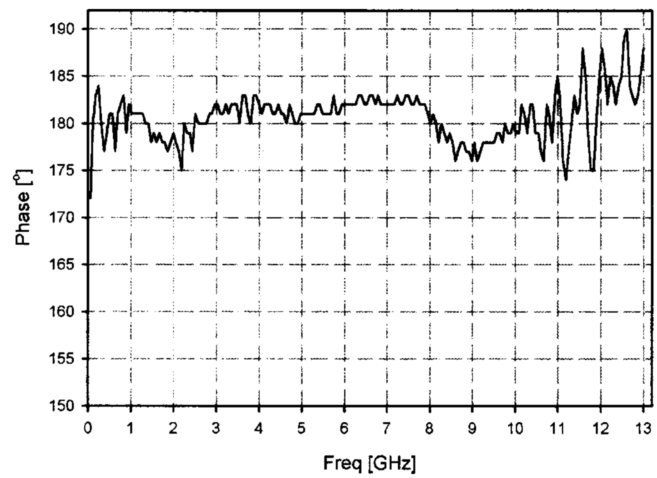

FIG. 7. Relative phase between the two end-to-end balun circuits; the 180° phase shift confirms the transformation of a balanced signal at the twin leads to an unbalanced signal at the 50 Ω microstrip ports.

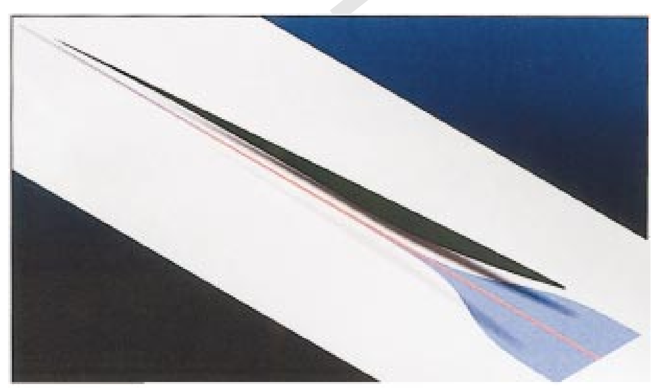

FIG. 8. (Color) Rendering of a resistive card vane (green) over balun (blue/red) for attenuating unwanted modes within a conducting enclosure.

(ε=9.6), which can reduce its length by more than a factor of 3. By making the tapered microstrip balun as short as possible, one can minimize the noise contribution due to ohmic loss. This is especially important when designing a high sensitivity log periodic fronted, where it is desirable to locate cooled GaAs or InP MMIC amplifiers as close as possible to the antenna terminals. In the Cuflon balun (ε=2.1), the twin-lead impedance matching section and the balun transducer were optimized as separate circuits, resulting in a total circuit length of ~10 in. By closely integrating the impedance matching and mode filtering function, it is possible to design a 500 MHz–11.2 GHz balun on a 0.020 in. quartz substrate which is 3.7 in. in length. Simulations of the terminated balun show the VSWR is $<$1.2, which is a good match to the LP antenna VSWR (~1.3). The balun transforms the antenna impedance to some value which provides the best achievable noise match when the unbalanced balun port is directly wire-bonded to a cooled MMIC amplifier.

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