A Broad-Band E-Plane 180° Millimeter-Wave Balun (Transition)

R. W. Alm, *Student Member, IEEE*, and R. Jennifer Hwu, *Member, IEEE*

***Abstract*—A broad-band 180° millimeter-wave balun has been developed using E-plane techniques which provides a practical transmission line transition suitable for many millimeter-wave integrated circuit applications. A novel dual-transition approach was taken that provides a transition from a standard rectangular waveguide to a balanced pair of narrow coplanar striplines. In this experiment, a Ka-band (26.5–40 GHz) balun was designed to provide a 100 Ω coplanar strip (balanced) output. Bandwidth performance was excellent with less than 2 dB of variation over the full waveguide band.**

I. Introduction

As MILLIMETER-WAVE designs become more and more sophisticated, there is a growing need for techniques which will allow multiple waveguide signals to be efficiently coupled to very small integrated circuit designs over wide bandwidths. This letter describes a novel approach to this problem in the development of a full waveguide bandwidth 180° "balun" (or transition) using E-plane technology which provides a very compact balanced line output which can be extrapolated for use over any waveguide frequency band.

II. Concept and Approach

The design of this 180° balun is actually a waveguide-to-balanced coplanar stripline adapter which is based on the principles outlined by Beyer and Wolff [1] in the construction of slotline, stripline, microstrip and coplanar waveguide transitions using E-plane (finline) techniques. In this case, however, a dual transition is designed which first provides a waveguide-to-slotline transition, followed by a constant impedance taper that adapts the slotline (with a semi-infinite ground plane extent) to a narrow balanced parallel coplanar-strip structure suitable for use in the tight confines of MIC and MMIC topologies. The narrow coplanar strips occupy only a fraction of the space required by a slotline structure with its large grounding areas.

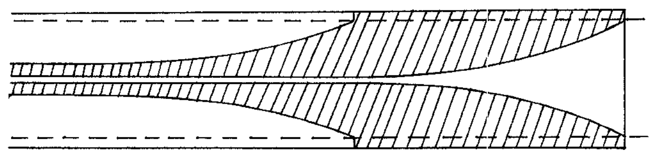
Since the energy is launched into the finline structure from opposite waveguide walls with opposing polarity currents, the 180° phase shift is achieved between the two coplanar-strip output lines over the full bandwidth of the input waveguide structure.

The term "balun" generally refers to a structure that converts a single-ended signal into a balanced configuration. One does not normally think of waveguide as a single-ended medium, nevertheless the typical laboratory interface to waveguide equipment is through the use of waveguide-to-coax adapters, which do indeed yield single-ended interfaces. This structure thus takes the place of the traditional adapter and provides a balanced output from the waveguide source as if a balun were employed. The term "balun" is thus used rather loosely here, where the term "transition" might be more appropriate.

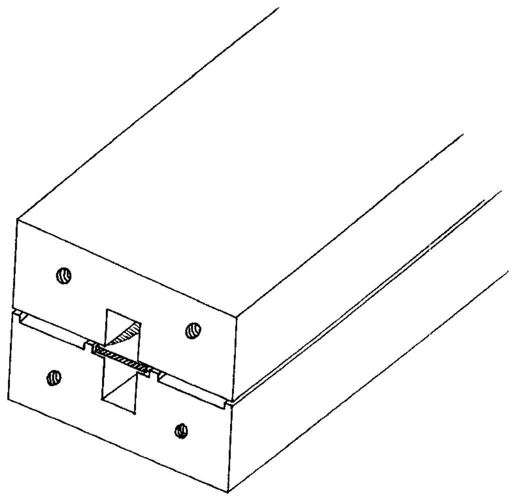
Manuscript received May 7, 1992.

The authors are with the Department of Electrical Engineering, University of Utah, 3376 E. 3900 S, Salt Lake City, UT 84124.

IEEE Log Number 9204126.



(a)



(b)

Fig. 1. (a) Metallization pattern used in the fabrication of the waveguide-to-slotline and slotline-to-balanced line transitions. The regions outside of the dotted lines indicate the ground contact zones. (b) End view of the split-block housing showing the placement of the Duroid circuit board in the E-plane of the rectangular waveguide.

III. Design and Fabrication

Fig. 1(a) shows an exaggerated view of the circuit pattern that was fabricated for the waveguide-to-slotline and slotline-to-coplanar stripline transitions. A high dielectric constant circuit board material ($\epsilon_r = 10.2$) was chosen in this case only because the authors were interfacing to a GaAs substrate ($\epsilon_r = 12.9$), and the circuit board was mounted in the E-plane of the waveguide as shown in Fig. 1(b). The ribs indicated in Fig. 1(b) were provided to ensure a good ground connection and to

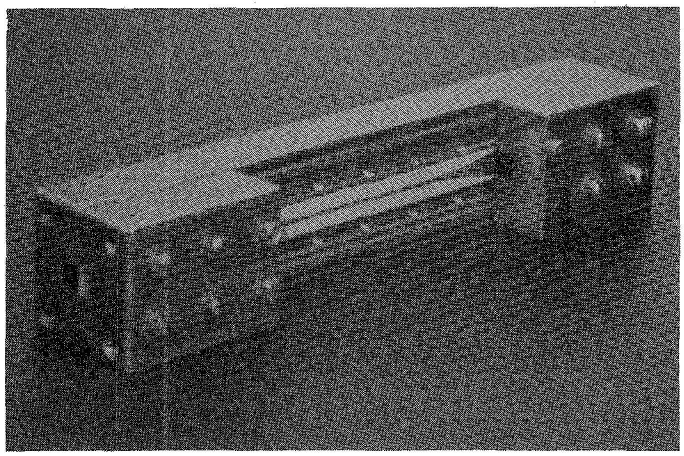


Fig. 2. Photograph of the back-to-back balun (transition) structure showing the input and output waveguide sections and 1.2 in of balanced coplanar strip transmission line.

maintain a continuous path for the currents in the waveguide walls.

The circuit was designed to operate over Ka-band (26.5–40 GHz) using standard rectangular WR-28 waveguide dimensions. The author has found [2] that waveguide taper and termination structures yield VSWR values of less than 1.05:1 when the taper lengths exceed 1.0 λ_g. For the case of the input waveguide-to-slotline transition, the effects of the thin Duroid board were ignored and the guide wavelength (λ_g) was assumed to be equal to λ_g for the WR-28 waveguide. At the lower band edge (26.5 GHz), $\lambda_g = 0.736$ in, and the taper length was chosen to be 0.9 in, or 1.25 λ_g.

At the end of the first transition, the propagating energy has been coupled into the E-plane circuit and is confined primarily in the slot region between the two surface ground planes. At this point, the waveguide housing is truncated as shown in Fig. 2. Beyond the end of the waveguide, a slot is provided beneath the coplanar stripline to eliminate ground-plane effects, but at a depth which is insufficient to support any propagating waveguide modes. The waveguide slot in the truncated waveguide section is also reduced in depth over the final 0.100 in of its length to cut off the propagating waveguide modes and prevent any direct radiation from waveguide to waveguide between the back-to-back transitions shown in Fig. 2.

The second transition, which adapts the slotline at the end of the first transition to the balanced coplanar stripline configuration, was also made to be approximately 1.0 λ_g in length. In this case, however, the fields are transitioned to a two wire transmission line (coplanar strips) where the wavelength is related to ϵ_{eff}, which can be approximated as [3]

$$\epsilon_{\text{eff}} \approx \frac{\epsilon_r + 1}{2}\left[\frac{\left(\frac{b}{t}\right)}{1+\left(\frac{b}{t}\right)}\right], \tag{1}$$

where b is the overall transmission line width including the gap spacing, t is the thickness of the Duroid board (0.010 in), and ϵ_r is the relative dielectric constant of the material (10.2). This is a reasonable approximation, since $\epsilon_{\text{eff}} \approx [\epsilon_r + 1]/2$ for narrow lines ($b/t < 3$) and $\epsilon_{\text{eff}} \to 1$ for $b/t \to \infty$. At the beginning of this transition, b/t is very large, and $\epsilon_{\text{eff}} \approx 1$, in which case $\lambda_{\text{eff}} = 0.446$ in at 26.5 GHz. At the end of the transition, $b/t = 2.2$, and from (1), ϵ_{eff} was calculated to be 2.7 and $\lambda_{\text{eff}} = 0.271$ in. Since the transition must be designed for the lowest value of ϵ_{eff}, the taper was made to be 0.7 in in length, which corresponds to 1.5 λ_g at 26.5 GHz.

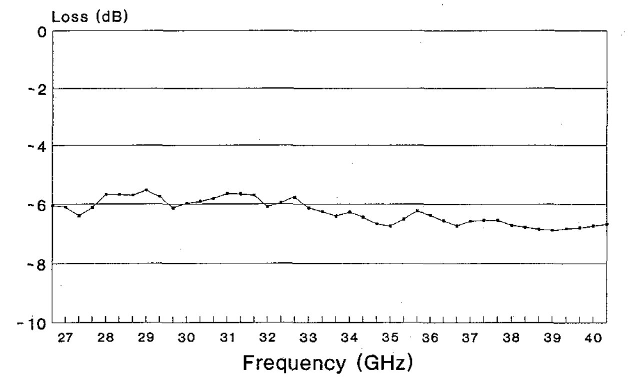


Fig. 3. Plot of the measured frequency response and insertion loss for two back-to-back balun structures (transitions). Overall loss includes the effects of 1.2 in of transmission line between the two back-to-back baluns (transitions).

The balanced-line output from the second transition was designed for a characteristic impedance (Z_o) of 100 Ω. It can be shown that for a parallel two-conductor transmission line on a dielectric medium (coplanar strips), the characteristic impedance is given by [3]

$$Z_o = \frac{591.7}{\sqrt{\epsilon_{\text{eff}}}\,\ln\left(\frac{8b}{\pi S}\right)}. \tag{2}$$

In this experiment, conductor line widths (W) of 0.010 in were selected, which required the fabrication of a 0.002-in gap (S) between the conductors to achieve a 100-Ω impedance. The 180° phase shift that is achieved through the launching method is independent of the impedance of the coplanar strip transmission line, thus any impedance may be used within reasonable fabrication limits. Impedance values lower than 100 Ω require gap dimensions smaller than may be practical for Duroid boards, and values higher than 200 Ω may be undesirable due to ohmic losses or radiation.

IV. Electrical Test Results

Two back-to-back transitions were fabricated in the waveguide/coplanar-balanced line/waveguide configuration shown in Fig. 2 for testing and evaluation. The fixture was first tested without the Duroid board inserted to measure the waveguide port-to-port isolation which was found to be 35 dB.

A total of 1.2 in of balanced coplanar stripline was included between the two end-to-end transition pairs. The frequency response and insertion loss was measured over the full waveguide bandwidth for the resulting structure, which measured 4.0 in in length. A plot of the response is shown in Fig. 3.

A single transition with a 100 Ω chip resistor connected across the balanced line was inserted into one end of the fixture so that the VSWR could be measured for a single balun (transition). Measurements were made at 28, 33, and 38 GHz using a slotted-line. The measured values were 1.22:1, 1.44:1, and 1.67:1, respectively, indicating that the 100 Ω load resistance was indeed close to the designed 100 Ω Z_o for this line.

The measured losses indicated in Fig. 3 were higher than anticipated. Some of the loss was due to a noticeable alignment error in the split block waveguide sections and a substantial roughness in the machined parts. Also, the etched circuit board was not plated after etching, and there was some error and nonuniformity in the 2-mil gap. Improving these conditions would most certainly reduce the losses.

The use of a high dielectric material E-plane circuit board may also lead to higher losses. On the other hand, if a low dielectric material were used, radiation losses would no doubt increase.

The second transition, which converts the slotline to the coplanar strips may radiate when the terminating impedance on the coplanar line is uncontrolled. Narrow-band radiation effects have been observed when the output coplanar strips were driving an uncontrolled impedance such as a mixer, but the effect was easily moved (in frequency) or eliminated by changing the load impedance. When a broad-band termination was provided, there was no measurable difference in radiation levels between the transition section and the coplanar strips themselves.

In considering the absolute loss level of around 6 dB as indicated in Fig. 3, it is important to keep in mind that this data represents two balun transitions plus 1.2 in. of the 100 Ω balanced coplanar stripline, which equates to nearly three wavelengths at the upper band edge. It is anticipated that a well-machined fixture with minimum transition and line lengths should yield a balun (transition) design with under 2 dB of loss per transition.

V. Conclusion

A broad-band 180° millimeter-wave balun was constructed as a waveguide-to-balanced coplanar stripline transition which should be applicable in wide variety of applications where space is limited. The design makes an ideal laboratory interface between existing equipment and new design topologies. The structure is based on E-plane (finline) techniques and is easily realizable. Other important features of this design include broad-band behavior with a natural 180° phase difference, a planar balanced-line configuration that lends itself nicely to integrated circuit topologies, and the capability to scale the approach to any waveguide band frequency including higher millimeter-wave frequencies.

References

[1] A. Beyer and I. Wolff, "Finline taper design made easy," *IEEE MTT-S Int. Microwave Symp. Dig.*, 1985, pp. 493–496.

[2] R. W. Alm, "Harmonic mixers elevate spectrum analysis to EHF," *Microwaves and RF*, vol. 20, no. 4, pp. 67–69, Apr. 1981.

[3] O. P. Gandhi, *Microwave Engineering and Applications.* New York: Pergamon Press, 1981, p. 62.

[4] S. Cohn, "Slot line on a dielectric substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, no. 10, pp. 768–778, Oct. 1969.