A Broad-Band Balanced HEMT Frequency Doubler in Uniplanar Technology

Andrey S. Yanev, Bogdan N. Todorov, and Vancety Z. Ranev

***Abstract*—Design and performance of a simple balanced high electron-mobility transistor doubler in uniplanar technology are described. The uniplanar in-phase and out-of-phase T-junctions with 2-octave bandwidth and a hybrid ring coupler with more than octave bandwidth have also been developed and investigated as a part of the doubler circuits. Measurements show more than 3-dB conversion gain, effective fundamental- and odd-harmonics suppression (>25 dB) in octave bandwidth (output frequency from 6 to 12 GHz), and maximum conversion gain of 8.8 dB at 3-dBm-input power level. The uniplanar design and simplicity of the circuit itself make the proposed frequency doubler suitable for monolithic-microwave integrated-circuit fabrication in millimeter-wave range.**

***Index Terms*—Balanced doubler, coplanar waveguides, HEMT, uniplanar technology.**

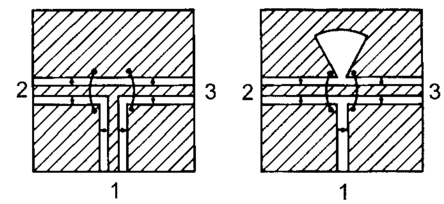
I. Introduction

BALANCED configurations are especially attractive in design of frequency doublers due to their inherent isolation in the output port from fundamental and odd harmonic signals. There exists a great need of broad-band balanced uniplanar balun structures useful in monolithic circuits. The different types of planar hybrid-ring couplers and baluns have been proposed by many authors and used for realization of broad-band balanced Schottky-diode doublers [1]–[4] with conversion loss less than 10 dB. Recently, there has been interest in FET multipliers to increase the conversion efficiency. Many balanced configurations have been demonstrated using FET's as a nonlinear elements [5]–[7]. However, current designs either show narrow-band operation or are not compatible with monolithic processes.

In this paper, we present a simple balanced high electron-mobility transistor (HEMT) doubler in purely uniplanar technology, which features conversion gain over broad-band operation, effective suppression of the fundamental and odd harmonics, and easy realization in hybrid and microwave integrated circuit (MIC) technology.

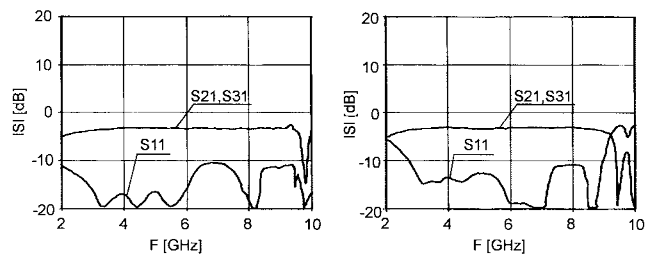
II. Uniplanar In-Phase and Out-of-Phase T-Junctions and Hybrid Ring Coupler

To confirm the wide-band behavior of the fundamental multiplier components, the coplanar waveguide (CPW)/CPW and slotline/CPW T-junctions were designed and investigated. Fig. 1 shows this circuit configuration and schematic diagram of the E-field distribution. The E-field in the CPW port 1 produced two CPW waves at ports 2 and 3 with E-field in the same direction [see Fig. 1(a)]. In Fig. 1(b), the E-field in the slot-line arm causes opposite E-field distribution in arms 2 and 3. In this way the input signal (port 1) is divided exactly in-phase or out-of-phase in infinite frequency bandwidth.



(a) (b)

Fig. 1. Circuit configuration and schematic diagram of E-field distribution for (a) in-phase CPW/CPW and (b) out-of-phase slotline/CPW T-junction.



(a) (b)

Fig. 2. Measured frequency response of power dividing ($S21$), ($S31$) and return loss ($S11$). (a) In-phase and (b) out-of-phase T-junction.

The T-junctions were designed for central-frequency 6 GHz and build on 1.27-mm-thick R/Duroid 6010.8 substrate with characteristic impedance of CPW feed line 1 and CPW output lines 2 and 3 [see Fig. 1(a)] $Zc = 50$ and $Zc = 70.7\ \Omega$, respectively, characteristic impedance of slot-line 1 and CPW lines 2 and 3 [see Fig. 1(b)] $Zc = 50\ \Omega$ and 35.4 Ω (series equivalent connection), respectively, slot-line radial stub angle 60°, and stub radius 3.4 mm.

Fig. 2 shows the measured frequency response of the power dividing and return loss. Power dividing less than 4 dB for in-phase and 4.5 dB for 180° reverse phase T-junction was achieved in 2–9-GHz band. Over the same frequency range, the maximum amplitude and phase difference are 0.4 dB and 3°. The return loss ($S11$) is less than −10 dB.

In order to demonstrate the feasibility of using the investigated T-junctions in wide-band circuit development, a simple uniplanar hybrid ring coupler have been designed and

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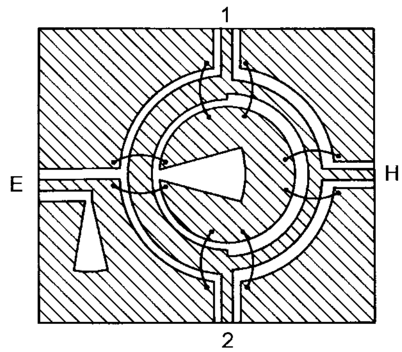
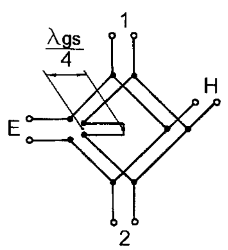
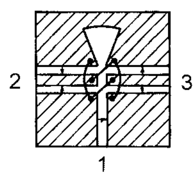


(a)





(b) (c)

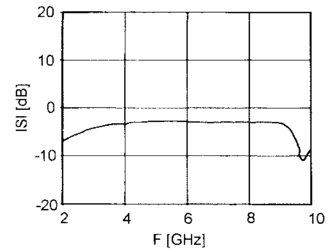
Fig. 3. (a) The uniplanar hybrid-ring coupler configuration. (b) Equivalent transmission-line model. (c) Circuit configuration of slotline CPW T-junction modification.

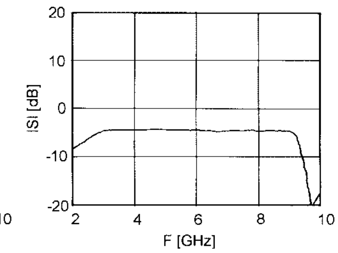
measured. The coupler configuration, consisting of a CPW ring with one slotline and three CPW feeds and the equivalent transmission-line model are shown in Fig. 3. The slotline/CPW T-junction is used as 180° phase inverter, which is represented as series-connected transmission lines in Fig. 3(b). A computer program based on the equivalent transmission-line model was developed and used to calculate the CPW ring dimension for minimum insertion loss of the in-phase and out-of-phase mode coupling.

The coupler was built on 1.27-mm-thick RT/Duroid 6010.8 substrate with the following dimensions [see Fig. 3(a)]:

1) CPW conductor and gap width of the feed lines $w = 0.7$, $g = 0.3$ mm;
2) slotline width $s = 0.15$ mm;
3) CPW conductor and gap width of out-of-phase ring arms $w = 0.9$, $g = 0.2$ mm;
4) CPW conductor and gap width of the in-phase ring arms $w = 0.5$, $g = 0.4$ mm;
5) slotline radial stub radius and angle $r = 3.4$ mm, $\theta = 60°$.

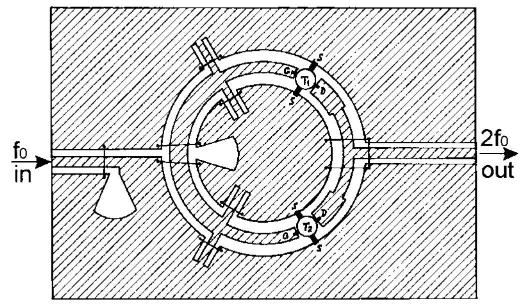
The experimental results show that the bandwidth of the reverse phase coupling in the hybrid is comparable to that of the T-junction itself [see Fig. 1(b)], while in phase coupling is limited to less than an octave. That is because the radial slotline stub in the out-of-phase junction is not effective open circuit at lower ($r \rightarrow \lambda/8$) and higher frequencies ($r \rightarrow \lambda/2$). The slotline/CPW junction was replaced by the modified junction shown in Fig. 3(c). The modification leads to 180° phase reverse of the signal propagated from ports 2 to 3 and vice versa in wider frequency band than the original T-junction [see Fig. 1(b)]. Thus, the bandwidth was extended up to 1.5 octave. Fig. 4 shows the power dividing of E- and H-arms. The



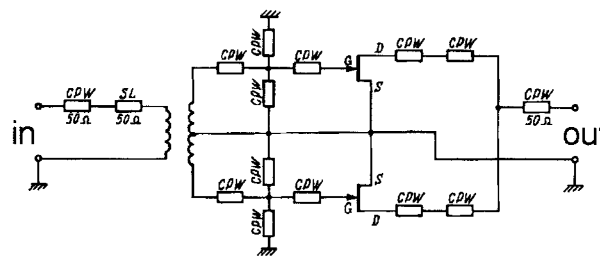


(a) (b)

Fig. 4. Measured frequency response of the hybrid-ring coupler. (a) H-arms power dividing ($S1H$), ($S2H$). (b) E-arms power dividing ($S1E$), ($S2E$).



(a)



(b)

Fig. 5. (a) Layout of balanced HEMT doubler. (b) Equivalent transmission-line model.

insertion loss of E- and H-plane power dividing are less than 1 and 1.5 dB, respectively, in the frequency band of 3–9 GHz. The power and phase balance in the same frequency band are less than 0.5 dB and 3°. The isolation between the E- and H-arms is greater than 26 dB.

III. Doubler-Circuit Design and Experimental Results

The doubler circuit realized on a 1.27-mm-thick RT/Duroid 6010.8 substrate is shown in Fig. 5. The input signal is applied to the transistor gates with 180° difference by using the slotline/CPW junction [see Fig. 1(b)]. Since the second and higher order even harmonics are generated by the two transistors in phase, these harmonics are extracted through an in-phase junction. The input signal and odd harmonics propagate along CPW lines out-of-phase and they are decoupled to the output port. The drain and gate terminals of the packaged transistors (OKI's KGF1870) are connected to the central conductors of the CPW lines. The sources are grounded. The input and output matching networks are realized in purely CPW techniques as two series transformers. The symmetrical parallel short CPW

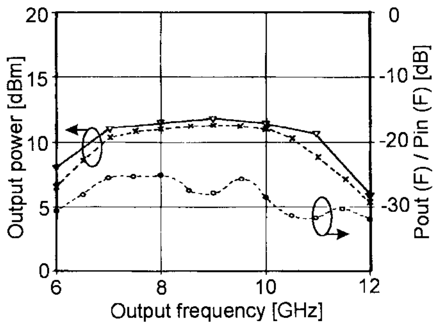


Fig. 6. Second harmonic output power and fundamental signal suppression versus frequency with an input power level of 3 dBm: ∇—simulated; $\backslash circ$, ×—measured.

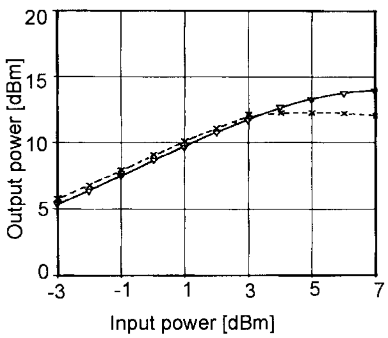


Fig. 7. Second harmonic output power versus input power level $f_{\rm in} = 4.5$ GHz: ∇—simulated; ×—measured.

stubs in the input-matching circuit serves also to connect transistor gates to the ground.

A nonlinear transistor model was constructed using the modified Materka model supported within Compact Scout. The model parameters extracted by fitting the model response to the measured dc and S-parameters and equivalent input and output matching circuits [see Fig. 5(b)] were used in a harmonic-balance simulation of the doubler. The dimensions of the gate and drain CPW circuits were optimized to provide a good match at fundamental and second harmonic frequency and maximum conversion gain at low input power levels (<3 dBm). The start dimensions of the CPW transmission lines used in nonlinear optimization were obtained from the linear matching optimization using measured S-parameters.

Using the above described circuit structure and design, an MIC frequency doubler has been fabricated and tested. Fig. 6 shows the simulated and measured output power and measured fundamental signal suppression in dependence on frequency with an input power level of 3 dBm. Conversion gain of more than 3 dB was measured in a 6–12-GHz frequency band. Maximum gain of 8.8 dB and output power of 15 mW were achieved at the central frequency. It can be seen that the measured power characteristic agrees well with the theoretical prediction. The fundamental frequency suppression at the output port was found to be more than 25 dB. This data is much less than predicted by the nonlinear simulation because the difference in transistor parameters and parasitic power leakage is from the input to output. The isolation may be improved by the selection of the transistor characteristics. The input voltage standing-wave ratio (VSWR) is less than 2.5 : 1 in the frequency band of the doubler.

The measured and simulated dependence of the output power on the input power level at the middle band frequency is given in Fig. 7. Measured power agrees closely with predicted results at input power levels less than 4 dBm. The discrepancy at the powers higher than 4 dBm may be coursed by inaccuracy in modeling the transistor nonlinearities in the range of the positive gate–source voltages.

IV. Conclusion

A novel wide-band balanced MIC multiplier in uniplanar technology have been proposed. The output CPW/CPW and input slotline/CPW T-junctions were used as in-phase and out-of-phase dividers. A 3-dB conversion gain and more than 25-dB fundamental frequency suppression at the output were measured in 6–12-GHz output frequency band. The frequency doubler shows maximum conversion gain of 8.8 dB near the middle-band frequency.

This uniplanar technique is promising for MMIC fabrication in millimeter-wave range.

References

[1] H. Ogawa and A. Minagawa, "Uniplanar MIC balanced multiplier—A proposed new structure for MIC's," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-35, pp. 1363–1368, Dec. 1987.

[2] S. A. Maas, "A broad-band, planar, monolithic resistive frequency doubler," in *IEEE MTT-S Dig.,* San Diego, CA, May 23–27, 1994, pp. 443–446.

[3] D. Filipovic, R. Bradley, and G. Rebeiz, "A planar broad-band MIC balanced varactor doubler using a novel grounded CPW to slotline transition," in *IEEE MTT-S Dig.,* San Diego, CA, May 23–27, 1994, pp. 1633–1636.

[4] R. Bitzer, "Wideband balanced frequency doublers—A proposed novel planar MIC structure," in *21st European Microwave Conf.,* Stuttgart, Germany, Sept. 9–11, 1991, pp. 334–338.

[5] I. Angelov, H. Zirath, N. Rorsman, and H. Grongvist, "A balanced millimeter wave doubler based on pseudomorphic HEMT's," in *IEEE MTT-S Dig.,* Albuquerque, NM, 1992, pp. 353–356.

[6] M. Tuko and I. Wolff, "Novel 36-GHz GaAs frequency doublers using (M)MIC coplanar technology," in *IEEE MTT-S Dig.,* Albuquerque, NM, 1992, pp. 1167–1170.

[7] Y. Xuan and J. Fukart, "Computer-aided design of microwave frequency doublers using a new circuit structure," *IEEE Trans. Microwave Theory Tech.,* vol. 41, pp. 2264–2268, Dec. 1992.

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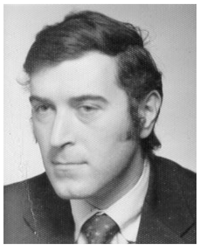

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