with a single, cooled, multiport, p-i-n diode switch can provide the following advantages with a minimal noise temperature:

1) elimination of interconnecting cables and connectors between switches and their ensuing loss and reliability difficulties,
2) reduction in space requirements and simplification of system component arrangement, and
3) improved cool-down time due to reduction in thermal mass.

Further improvement in the noise temperature of cooled p-i-n diode switches can probably result from a more judicious selection and impedance matching of the p-i-n diodes. However, information regarding p-i-n diode characteristics at cryogenic temperatures seems to be unavailable, indicating a need for additional work in this area.

ACKNOWLEDGMENT

The author wishes to thank Dr. S. Weinreb of NRAO for suggesting the original switch configuration and T. Wojtowicz, formerly of NRAO, for providing help with the package design. Thanks are also extended to the following employees of NRAO: J. Coe for assisting with the measurements, B. Wright for the excellent machining, A. Miano for preparing the art work and drafting, and C. Dunkle for typing the manuscript.

REFERENCES

[1] J. Coe, "NAIC Receiver," Electronics Division Internal Report No. 180, National Radio Astronomy Observatory, Green Bank, WV, Oct. 1977.
[2] R. Turner, "A low loss coolable switch for Dicke radiometers," thesis University of Virginia, Charlottesville, VA, Aug. 1972.
[3] J. D. Kraus, *Radio Astronomy*. New York: McGraw-Hill, 1966, pp. 248–254.
[4] R. H. Dicke, "The measurements of thermal radiation at microwave frequencies," *Rev. Sci. Instr.*, vol. 17, pp. 268–275, July 1946.
[5] Hewlett–Packard Data Sheet on 5082-3141 PIN diodes.

Subharmonically Pumped Schottky Diode Single Sideband Modulator

JERZY CHRAMIEC

***Abstract*—A subharmonically pumped single sideband Schottky diode modulator is described. Its advantages are a large carrier suppression and lowered pumping frequency. The experimental 2-GHz MIC modulator pumped with an 8-mW signal exhibits a conversion loss of 6.2–7.3 dB over a 15-percent frequency band. For a 120-μW input modulating signal, the unwanted components in the output spectrum are at least 18 dB and mostly over 20 dB below the desired sideband.**

I. INTRODUCTION

SEVERAL types of microwave single sideband (SSB) modulators are known. The fundamental method of suppressing one sideband consists in the filtering of the output signal of a double sideband (DSB) modulator. This scheme however has practical limitations for low modulating frequencies and for systems with variable carrier and/or modulating frequency. In such cases balanced SSB modulators may be used, following the principles described in [1] and [2] (Fig. 1). A balanced SSB modulator consists essentially of two DSB modulators and an appropriate dividing, phasing and summing network to suppress one of the sidebands as well as the carrier. Let us consider the conditions of generating a "true suppressed-carrier SSB signal," that is a signal with the carrier and one of the sidebands suppressed for instance by 20 dB with respect to the desired sideband. The sideband suppression factor in this example equals 20 dB and may be attained in either circuit of Fig. 1. The required carrier suppression factor A_p may be evaluated from the formula:

$$A_p[\text{dB}] \geqslant 20 + 10\log\frac{P_c}{P_m} + L_c \qquad (1)$$

where P_m is the modulating signal power, P_c is the carrier power, and L_c is the modulator conversion loss. Putting $(P_c)/(P_m) \geqslant 25$ (for linear operation), $L_c = 6$ dB, we get $A_p \geqslant 40$ dB. Such a high value of A_p may be obtained only when high-isolation directional couplers as well as perfectly paired and matched diodes are used. The purpose of this paper is to describe a SSB modulator which is

Manuscript received May 26, 1977; revised April 17, 1978.
The author is with University of Basrah, College of Engineering, Electrical Department, Basrah, Iraq.

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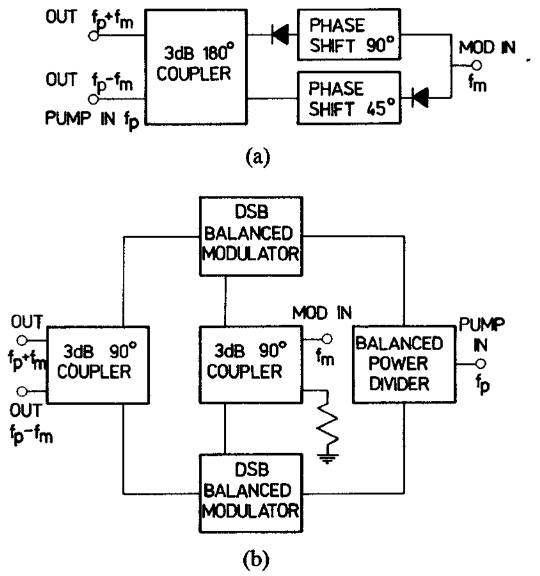

Fig. 1. Block diagrams of balanced SSB modulators.

pumped at a submultiple of the carrier frequency. This approach results in a high amount of carrier suppression if well-paired diodes are used. Because of lowered pump frequency, this circuit may also have some advantages if used as an upconverter at millimeter-wave frequencies.

II. Subharmonically Pumped SSB Modulator

The electrical properties of two antiparallel-mounted Schottky barrier diodes are used in the proposed circuit. The diode pair has an asymmetric current-voltage characteristic (Fig. 2) and its properties have been thoroughly analyzed in a number of papers on subharmonically pumped downconverters [3]–[6]. With a harmonic pump voltage v_p applied, the total current flowing through the diodes contains only the components at odd harmonics of the pump frequency $\omega_p = 2\pi f_p$. The parametric conductance contains only the zero-order term G_0 and the components at even harmonics of the pump frequency:

$$g(t) = \sum_{n=-\infty}^{\infty} G_{2n} e^{j2n\omega_p t}. \tag{2}$$

Now let a low-level modulating signal $v_m = V_m e^{j\omega_m t}$ be applied to the parametric conductance (2). The resulting output spectrum is shown in Fig. 3. It is seen that a suppressed-carrier DSB modulation (upconversion) has been obtained. The upconverter voltage waves emerging from the parametric conductance may be expressed as follows:

$$b^{(n)} = \sqrt{L_{cn}}\; V_m \left[e^{j(2n\omega_p - \omega_m)t} + e^{j(2n\omega_p + \omega_m)t} \right] \tag{3}$$

where L_{cn} represents the conversion loss. For purely resistive diodes the value of L_{cn} is equal to that of a corresponding downconverter. For example, for $n = 1$ and a perfect filtering of all higher order components in the output spectrum, the value of L_{c1} corresponds to that of a mixer with identical parameters at the signal and image frequency. The same holds for the input and output conductances, the conditions of optimum performance, etc. Thus all the results of the well-established Schottky

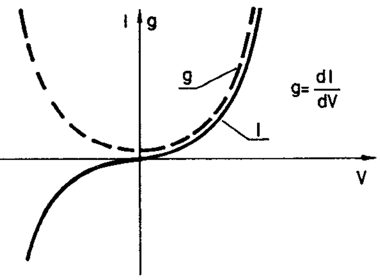

Fig. 2. Current-voltage and differential conductance characteristics of antiparallel Schottky diode pair.

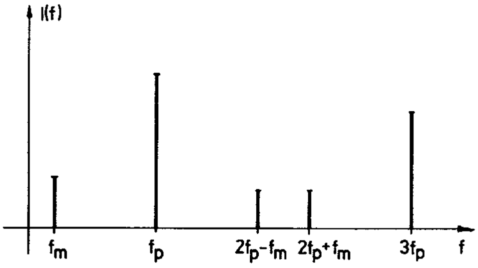

Fig. 3. Output current spectrum of antiparallel diode pair excited by harmonic pump and modulating signals.

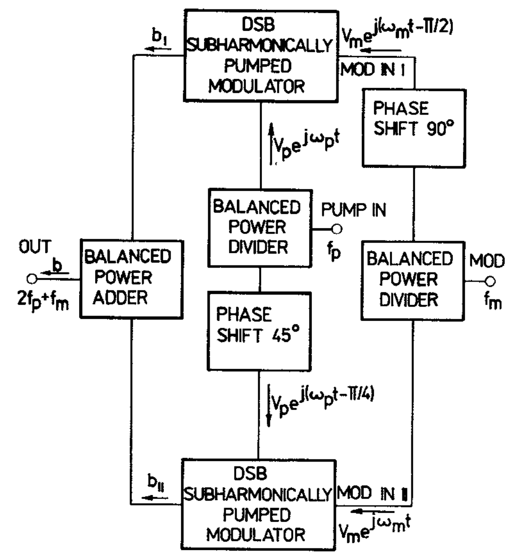

Fig. 4. Block diagram of subharmonically pumped SSB modulator.

diode downconverter theory [3]–[8] may be directly employed and they will not be cited here.

The complete SSB modulator circuit is shown in Fig. 4. It is quite similar to that of Fig. 1(b) with the difference that instead of 3-dB 90° couplers the balanced 3-dB power dividers or adders and the appropriate phase shifters are being used. Assume a perfect symmetry of the DSB modulators and let the power dividers be described by the scattering matrix:

$$S = -\frac{j}{2} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}. \tag{4}$$

With the use of (3) and (4), the voltage waves b emerging from the modulator may be calculated. Assuming $n=1$,

$$b=2\sqrt{L_{c1}}\; V_m e^{j(2\omega p+\omega_m)t}. \tag{5}$$

In this idealized case the output signal contains only the upper sideband. If the position of either phase shifter in Fig. 4 is changed, the lower sideband will be obtained. Similar properties are exhibited by the modulator circuit with the phase shifters removed and with all power dividers replaced by 3-dB 90° couplers. Upper and lower sidebands are then selected in the output coupler.

If the modulator circuit is to include filters eliminating the odd harmonics of the pump frequency, then its potential bandwidth is limited to less than one octave (for $n=1$); in the opposite case no theoretical bandwidth limitation exists. The great advantage of the described circuit is that the carrier suppression process is essentially frequency independent and relies upon the diode balance. It should be also noted, that the pump AM noise is suppressed at the modulator output in just the same way as in subharmonically pumped downconverters [6].

III. Effects of Diode and Circuit Unbalance

To evaluate the required diode and circuit balance, an appropriate simplified analysis has been performed. First, the effect of diode unbalance on the carrier attenuation has been calculated. The diodes were assumed to have slightly different exponents α and saturation currents J_s:

$$J_1=J_s(e^{\alpha V}-1) \qquad J_2=(J_s+\Delta J_s)\left[e^{(\alpha+\Delta\alpha)V}-1\right] \tag{6}$$

$$\frac{\Delta J_s}{J_s}\ll 1 \qquad \frac{\Delta\alpha}{\alpha}\ll 1.$$

The total current flowing through the antiparallel diode pair with the harmonic pump voltage applied had been then calculated with the use of modified Bessel functions. The analysis is quite similar to that of Henry *et al.* [6] and will not be presented here. The carrier suppression factor A_p is defined as a ratio of the average power absorbed in the diodes at the pump frequency f_p to the available output power at the frequency $2f_p$. For heavy pumping the following approximate expression has been found:

$$A_p[\mathrm{dB}]=10\log 2\alpha V_p\left[1+\frac{2}{\alpha V_p\dfrac{\Delta\alpha}{\alpha}+\dfrac{\Delta J_s}{J_s}}\right]^2 \tag{7}$$

or

$$A_p[\mathrm{dB}]=10\log 2\alpha V_p\left[1+\frac{2J_sJ_0(\alpha V_p)}{J_{dc}}\right]^2 \tag{8}$$

where $J_0(\alpha V_p)$ is the zero order modified Bessel function of the first kind and J_{dc} is the direct current flowing through the diode pair.

For an illustrative example, let us assume $\alpha V_p=20$, $\Delta\alpha/\alpha=\Delta J_s/J_s=0.02$. Then $A_p=31$ dB. An additional carrier attenuation of about 3 dB is obtained in the output power adder of Fig. 4. Furthermore, for heavy pumping the presence of diode series resistance widens the current pulses in each diode, reducing considerably the second harmonic content. For well-paired diodes the carrier attenuation of above 40 dB is therefore quite realistic.

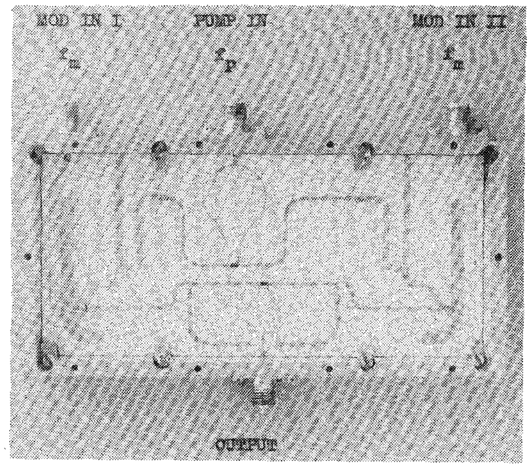

Fig. 5. Experimental 2-GHz modulator.

Now let us consider the effects of circuit phase and amplitude unbalance on the unwanted sideband suppression factor A_s. Assuming a perfect output power adder, the phase unbalance expressed in terms of phase deviations $\Delta\varphi_p$, $\Delta\varphi_m$ from the values given in Fig. 4 leads to the following value of A_s:

$$A_s[\mathrm{dB}]\simeq 10\log\frac{2}{1-\cos(2\Delta\varphi_p+\Delta\varphi_m)}. \tag{9}$$

For $2\Delta\varphi_p+\Delta\varphi_m+10°$, this results in $A_s=21$ dB.

The amplitude unbalance may be expressed in terms of the conversion loss difference of two DSB modulators. With a perfect output power adder one obtains:

$$A_s[\mathrm{dB}]\simeq 10\log\left[16\left(\frac{L_c}{\Delta L_c}\right)^2+8\frac{L_c}{\Delta L_c}\right]. \tag{10}$$

For $\Delta L_c/L_c=0.1$, this results in $A_s=32$ dB. The SSB modulator is thus much more sensitive to phase than to amplitude unbalance.

IV. Experimental Results

The experimental subharmonically pumped 2-GHz single sideband MIC modulator is shown in Fig. 5. It has been realized on an alumina substrate of 0.7-mm thickness. The Schottky barrier diodes employed in the two DSB subharmonically pumped modulators are silicon S-band devices mounted in standard leadless inverted device (LID) packages. Each DSB modulator contains the necessary matching and filtering circuits. The pump power balanced divider, the $\lambda_p/8$ phase shifter and the output power adder are realized on the central substrate. To prevent the modulators from interacting at the pump frequency through the output circuit, appropriate bandstop filters have been inserted between the modulators and the output power adder. The 35-MHz modulating signal is fed through a circuit shown in Fig. 6. It provides the required phase shift of the modulating signals applied

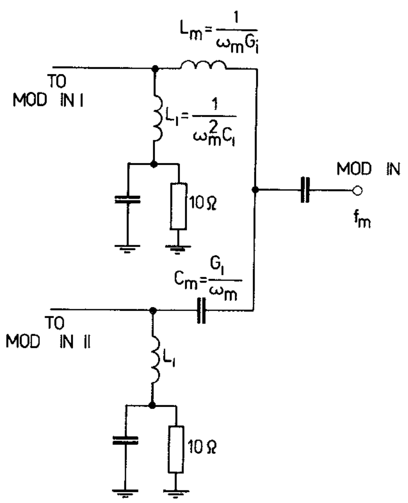

Fig. 6. Schematic of modulating signal input circuit. G_i is the DSB modulator input conductance; C_i is the DSB modulator input capacitance.

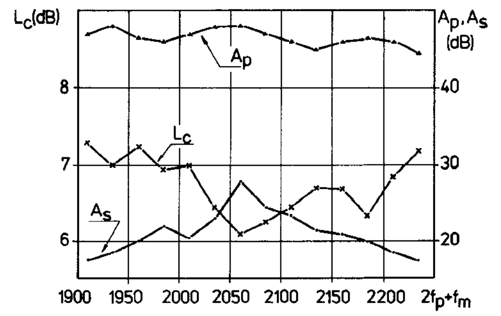

Fig. 7. Performance of the experimental SSB modulator. L_c is the conversion loss; A_p is the carrier suppression factor; A_s is the lower sideband suppression factor; $P_p = 8$ mW; $P_m = 120$ μW; $f_m = 35$ MHz.

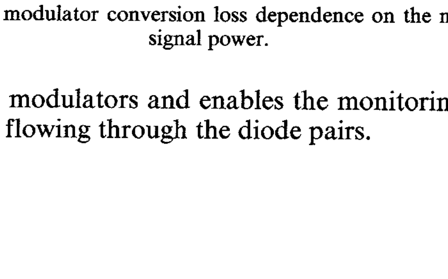

Fig. 8. SSB modulator conversion loss dependence on the modulating signal power.

to the DSB modulators and enables the monitoring of the dc currents flowing through the diode pairs.

Although all microwave circuits were designed at a central frequency of 2 or 1 GHz, quite good results have been obtained in the 15-percent frequency band. They are shown in Fig. 7 and include the measured values of conversion loss L_c, carrier suppression factor A_p, and lower sideband suppression factor A_s. Thus for the given values of the pump and modulating signal power, the unwanted lower sideband signals are down by at least 18 dB as compared to the upper sideband. The modulator linearity has been also measured and the results are shown in Fig. 8.

V. Conclusions

A simplified theory of a subharmonically pumped Schottky diode SSB modulator has been presented. The experimental 2-GHz upper sideband modulator pumped with an 8-mW signal shows in the 15-percent frequency band a conversion loss of less than 7.3 dB, the minimum value being 6.1 dB. For a 120-μW modulating signal, the unwanted output components are at least 18 dB below the upper sideband. These results show that the new circuit has a high amount of carrier and unwanted sideband suppression.

Acknowledgment

The author gratefully acknowledges the collaboration of K. Kniecinski in the design and measurements of the experimental modulator.

References

[1] J. L. Altman, *Microwave circuits*. NJ: Van Nostrand, 1964, p. 342.
[2] Anaren Microwave Inc., *1970 Product Catalog*, Mixer supplement, p. 15.
[3] J. D. Buchs, "Ein subharmonisch gesteurerter Schottky diodenmischer in Streifenleitungstechnik," *A.E.U.*, vol. 25, pp. 52–53, Jan. 1971.
[4] M. V. Schneider and W. W. Snell, Jr., "Harmonically pumped stripline downconverter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 271–275, Mar. 1975.
[5] M. Cohn *et al.*, "Harmonic mixing with an antiparallel diode pair," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 667–673, Aug. 1975.
[6] P. S. Henry *et al.*, "Local-Oscillator noise cancellation in the subharmonically pumped downconverter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 254–257, May 1976.
[7] M. R. Barber, "Noise figure and conversion loss of the Schottky barrier mixer diode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 629–635, Nov. 1967.
[8] G. B. Stracca, "On frequency converters using non-linear resistor," *Alta Frequenza*, vol. 38, pp. 313–331, May 1969.