A Study of *W*-Band Subharmonically Pumped Mixer

WANG YUN-YI AND SHU YONG-HUI

Abstract—A *W*-band subharmonically pumped mixer with packaged Schottky diodes has been developed. The design and performance of this mixer are described in detail. A new method for measuring the embedding network parameters of the subharmonically pumped mixer has been developed and the measurement has been carried out directly at $2f_{LO}$ and $2f_{LO} \pm f_{if}$. A special program for the analysis of the subharmonically pumped mixer has been developed, and computed results are given in comparison with measured results.

I. Introduction

THE KEY PROBLEM of accurate analysis and the design of a mixer is to determine the parameters of the embedding network. Since this network usually consists of complex circuits, it is difficult to determine its parameters through theoretical analysis. It has been proved that measurement is an applicable method. However, because of difficulties of measurement at the millimeter-wave band, most measurements were made with only a low-frequency scaling model and for only a single diode mixer [1], [2].

We have developed a *W*-band subharmonically pumped mixer with packaged Schottky diodes. The performance of this mixer, including conversion loss, noise ratio, and input VSWR in relation to LO power and/or frequency, has been measured. A new method for measuring parameters of the embedding network of the mixer has been developed and the measurements have been carried out directly at $2f_{LO}$ and $2f_{LO} \pm f_{if}$. From these measured parameters of the embedding network, the performances of the mixer have been computed with an analysis program of the subharmonically pumped mixer. Comparison between computed and measured results shows good agreement.

II. Design and Performances of the Mixer

As we have known, the subharmonically pumped mixer is attractive in the millimeter-wave band, especially at or above *W*-band, because it is more difficult to get a LO source with sufficient power at a very high frequency. In addition, the subharmonically pumped mixer has its inherent features and its performance is comparable with the fundamental pumped mixer. Therefore, the subharmonically pumped mixer in the short millimeter-wave band has been developed rapidly in recent years.

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The inherent advantages of the subharmonically pumped mixer can be summarized as follows:

a) no currents of $\omega_{LO} \pm \omega_s$ appear in the external circuit, so the noise caused by a LO source can be suppressed;
b) the conversion loss can be reduced;
c) the dc current flows only through the loop formed by the two diodes, so there is no need to consider the dc return in the circuit design;
d) since two diodes form a loop, they can prevent breakdown caused by backward voltage from each other.

A. Design of the Mixer

The configuration of the *W*-band subharmonically pumped mixer is shown in Fig. 1.

1) Diode: Because of the lack of beam lead diodes and substrate material suitable for the millimeter-wave band, we have to use packaged Schottky diodes. They are provided by the Nanjing Solid State Device Research Institute and the parameters are listed in Table I.

2) LO Low-Pass Filter: In general, suspended microstrip line is applicable for the design of millimeter-wave band filters. But, as explained above, since the packaged coaxial diodes have been applied, the best configuration of a LO low-pass filter should be coaxial. It is designed with a Chebyshev response and includes five stages. The radius of the outer and inner conductors of the coaxial line should be designed in accordance with following conditions:

$$a + b \leqslant \lambda_{\min}/\pi$$

and

$$b/a \doteq 3.5.$$

Finally, the dimensions of the coaxial low-pass filter are determined as shown in Fig. 2. The radius of the outer conductor of the coaxial line is 1.33 mm.

3) Backshort: Two backshorts are required for tuning in the *W*- and *Q*-bands. A perfect backshort is particularly important for the signal port because the loss of signal caused by a backshort will directly affect the conversion loss of the mixer. Brewer and Räisänen [3] have developed a noncontacting backshort based on the principle of the low-pass filter. According to this principle, a *W*-band

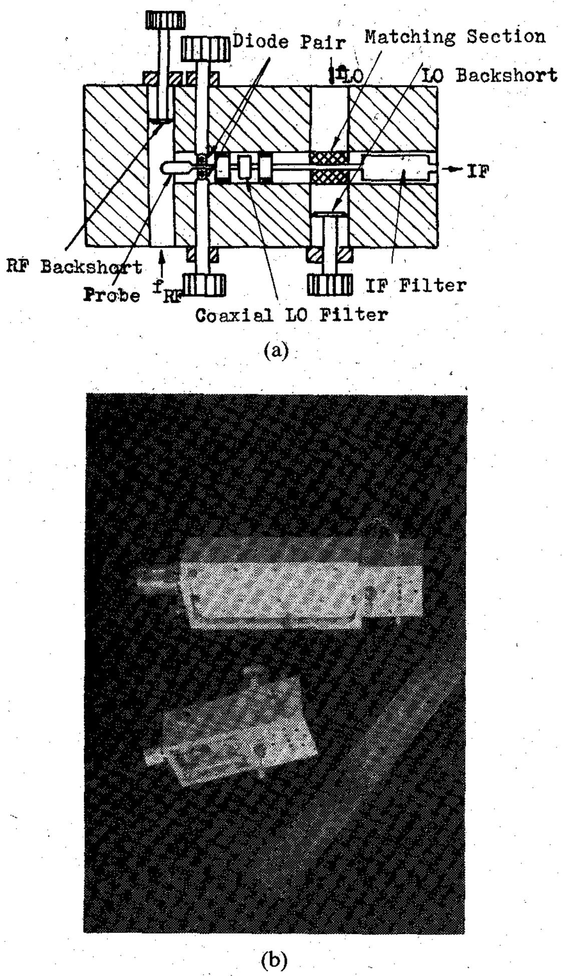

Fig. 1. Configuration of W-band subharmonically pumped mixer. (a) Configuration. (b) Photograph.

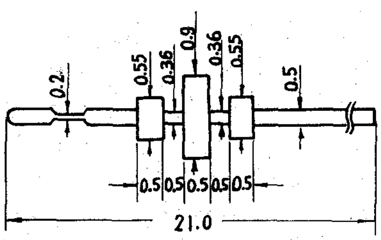

Fig. 2. Inner conductor of filter.

TABLE I
PARAMETERS OF THE DIODE

Para.	R_s (ohm)	L_s (nH)	C_p (pF)	C_j (pF)	V_B (V)	I_s (A)	ϕ (V)
	5.0	0.1	0.2–0.3	0.4	7–8	5×10^{-9}	0.75

backshort used for the subharmonically pumped mixer was designed and is shown in Fig. 3.

B. Performance of the Mixer

The performance of the W-band subharmonically pumped mixer, including conversion loss, noise ratio, and input VSWR, has been measured and listed in Table II. The conversion loss of the mixer in relation to frequency, LO power, and the backshort position of the signal port are shown in Figs. 4–6, respectively.

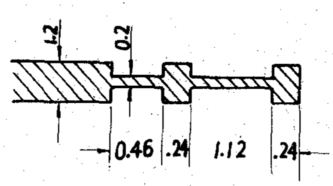

Fig. 3. W-band backshort.

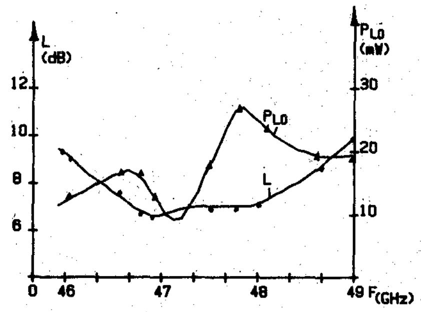

Fig. 4. Frequency response of the W-band subharmonically pumped mixer.

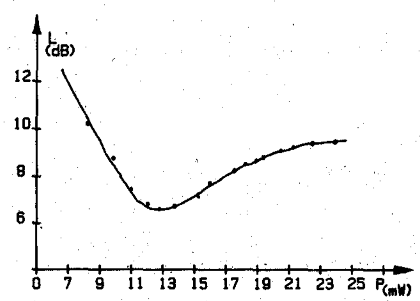

Fig. 5. Conversion loss versus LO power.

TABLE II
OPERATING FREQUENCIES AND PERFORMANCE OF THE MIXER

Mixer Para.	f_{LO} (GHz)	f_{if} (GHz)	L_c(DSB) (dB)	t_m ($\times$290K)	input VSWR	P_{LO} (mW)
	46.84	1.2	6.35	321.9	1.2	8–15

III. MEASUREMENT OF THE EMBEDDING NETWORK PARAMETERS

In order to analyze and design the mixer accurately, it is necessary to determine the parameters of the embedding network. In the past, most measurements of the embedding network parameters were made with a low-frequency scaling model and only for a single-diode mixer. Unfortunately, it is very difficult to realize the low-frequency scaling model for the subharmonically pumped mixer. Therefore, we have to develop a new method for measuring the parameters of the embedding network.

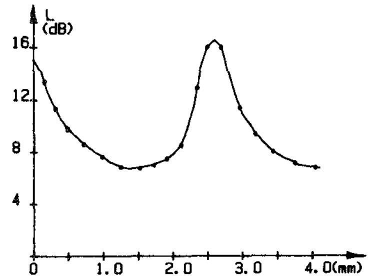

Fig. 6. Conversion loss of mixer is measured in relation to the position of the backshort of the signal port.

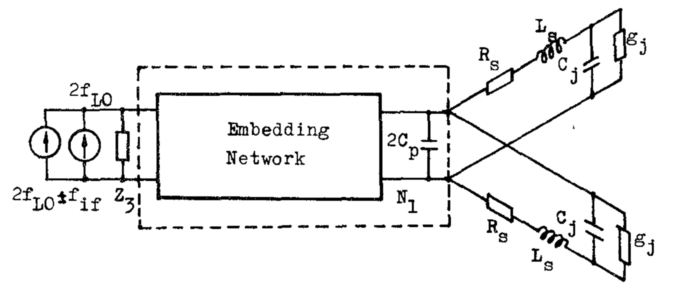

Fig 7. The equivalent circuit of the subharmonically pumped mixer.

A. Principle

Fig. 7 shows the equivalent circuit of the mixer. The embedding network includes the total circuit except the diodes. We put the package capacitance $2C_p$ of the two diodes with the embedding network together and form a two-port network N_1. If the parameters of network N_1 are known, the impedance seen from the junction of the diodes can be determined. Then the nonlinear and linear analyses of the mixer are possible to be carried out. In order to measure the parameters of network N_1, we take one adequately biased diode put in place as a variable reactive load of the two-port network N (see Fig. 8). At the same time, another diode is put in place but its junction is broken. Thus, the equivalent circuit for the measurement is shown as Fig. 8.

The biasing voltage of the diode taken as a variable reactive load of network N is changed from -5 V to 0.5 V and divided into 13 intervals in this range. Since the current through the diode is very small if the biasing voltage is less than 0.5 V, the junction conductance of diode can be neglected. The relationship between the input reflection coefficient Γ_{in} and the load reflection coefficient Γ_c of network N is given by

$$\Gamma_{in} = S_{11} + \frac{S_{12}^2 \Gamma_c}{1 - S_{22}\Gamma_c}. \tag{1}$$

With a variable biasing voltage, the reflection coefficient Γ_c caused by the junction capacitance C_j changes along the unit circle. The mapping of the Γ_c circle, the track of measured Γ_{in}, is also a circle. Three important points should be found for the determination of the network parameters (shown in Fig. 9).

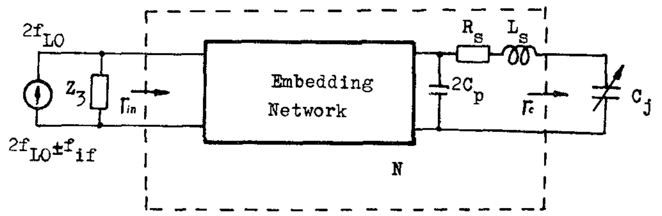

Fig. 8. The equivalent circuit for measurement.

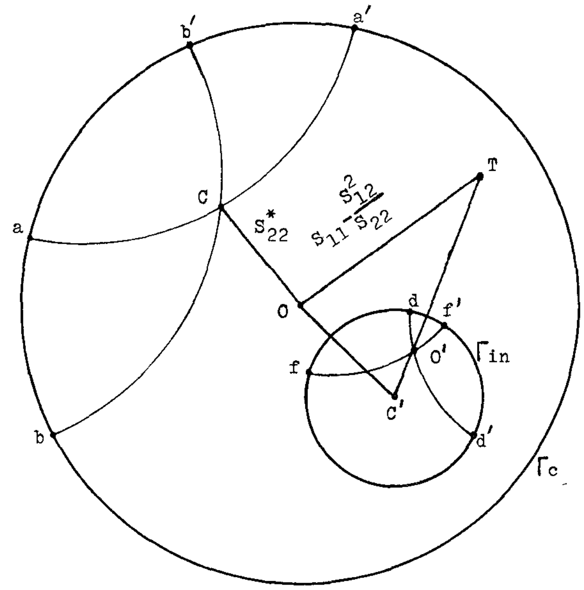

Fig. 9. The relation between locations of points O', C, and T and the scattering parameters.

1) O', the partial center of the Γ_{in} circle and the mapping of center O of Γ_c circle. Since $\Gamma_c = 0$ at point O, therefore

$$S_{11} = \overline{OO'}. \tag{2}$$

2) T, the symmetric point of O' in relation to the Γ_{in} circle. In accordance with theorem of the symmetric point invariance, Γ_c corresponding to point T must be symmetric with O in relation to the Γ_c circle, i.e., the mapping of T is $\Gamma_c = \infty$. From the substitution of $\Gamma_c = \infty$ in (1), the relationship is given by

$$S_{11} - \frac{S_{12}^2}{S_{22}} = \overline{OT}. \tag{3}$$

3) C, the mapping of center C' of the Γ_{in} circle. The symmetric point of C' in relation to the Γ_{in} circle is $\Gamma_{in} = \infty$. The mapping of $\Gamma_{in} = \infty$ is $\Gamma_c = 1/S_{22}$. Thus, the symmetric point of $\Gamma_c = 1/S_{22}$ in relation to the Γ_c circle is

$$S_{22}^* = \overline{OC}. \tag{4}$$

The radius of the Γ_{in} circle can be calculated from the scattering parameters of the network. That is

$$R = \frac{|S_{12}|^2}{1 - |S_{22}|^2}. \tag{5}$$

Now, the problem which remains to be solved is how to

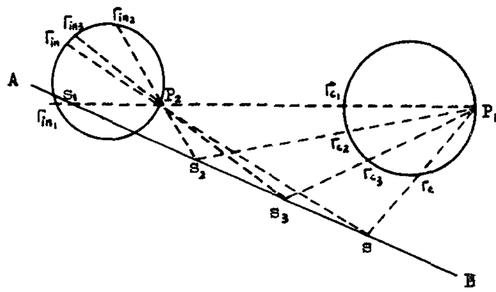

Fig. 10. Perspective centers and AB line determined from conformal transformation circles.

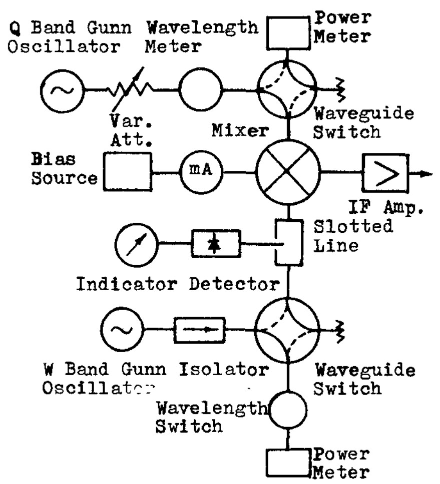

Fig. 11. Block diagram of the experimental system for the measurement of the embedding network parameters.

find three points O', T, and C from the measured Γ_{in} circle.

Equation (1) is a linear fractional conformal transformation. In accordance with the theorem of a four-point cross ratio [4], if we have known Γ_{in1}, Γ_{in2}, and Γ_{in3} corresponding to Γ_{c1}, Γ_{c2}, and Γ_{c3}, respectively, then Γ_{in} is related to Γ_c by

$$\frac{\Gamma_c - \Gamma_{c1}}{\Gamma_c - \Gamma_{c2}} \frac{\Gamma_{c3} - \Gamma_{c2}}{\Gamma_{c3} - \Gamma_{c1}} = \frac{\Gamma_{in} - \Gamma_{in1}}{\Gamma_{in} - \Gamma_{in2}} \frac{\Gamma_{in3} - \Gamma_{in2}}{\Gamma_{in3} - \Gamma_{in1}}. \tag{6}$$

The mapping of the Γ_c circle (or a straight line) in the Γ_{in} plane must be a circle (or a straight line). If Γ_{c1} and Γ_{in1} are connected and the cross points of the $\Gamma_{c1}\Gamma_{in1}$ line with the Γ_c and Γ_{in} circles are P_1 and P_2 (known as perspective centers, see Fig. 10), respectively; thus, the cross points S_1, S_2, and S_3 of lines $P_1\Gamma_{c1}$, $P_1\Gamma_{c2}$, and $P_1\Gamma_{c3}$ with $P_2\Gamma_{in1}$, $P_2\Gamma_{in2}$, and $P_2\Gamma_{in3}$ must lie on the same line AB. With line AB and perspective centers P_1 and P_2, Γ_{in} corresponding to given Γ_c can be found through a graphic method. It is the same the other way around. That is, connecting P_1 and given Γ_c, if the $P_1\Gamma_c$ line crosses the AB line at point S, the cross point of the P_2S line with the Γ_{in} circle is just Γ_{in} corresponding to given Γ_c.

Based on the principle described above, a graphic method for determination of the scattering parameters of the network from the measured Γ_{in} circle has been developed [5].

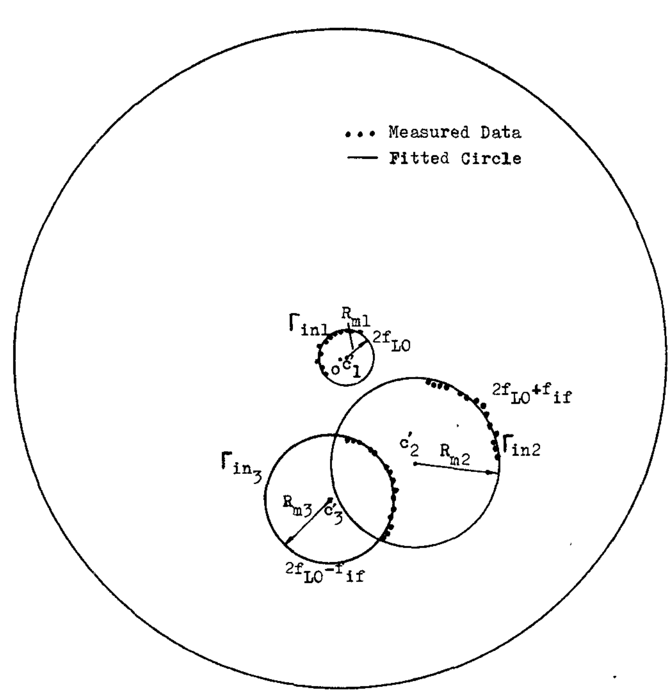

Fig. 12. The measured Γ_{in} circles at three frequencies.

Here it is used for determination of the embedding network parameters of a subharmonically pumped mixer.

Fig. 9 shows how to find three points O', T, and C from the Γ_c and Γ_{in} circles. At first, two diameters of the Γ_{in} circle are drawn (not shown in Fig. 9), then their mappings, i.e., $\widehat{aa'}$ and $\widehat{bb'}$, can be determined with the graphic method introduced above. The cross point C of $\widehat{aa'}$ and $\widehat{bb'}$ inside the Γ_c circle is the mapping of point C'. Similarly, partial center O' can be determined from the cross point of $\widehat{ff'}$ and $\widehat{dd'}$ inside the Γ_{in} circle, and point T is the cross point of $\widehat{ff'}$ and $\widehat{dd'}$ outside the Γ_{in} circle.

B. Procedure of the Measurement

At first, the subharmonically pumped mixer is adjusted with LO power and two backshorts to reach a minimum conversion loss, but no bias is applied. Then one of the diodes is replaced by a diode which has the same package but whose junction has been broken. Another diode is biased in the reverse direction and the biasing voltage is changed gradually from -5 V to 0.5 V. A W-band VSWR test system is connected to the signal port of the mixer. The block diagram of the experimental system for measuring the embedding network parameters is shown in Fig. 11. For a given biasing voltage C_j of the diode and Γ_c can be calculated and the input reflection coefficient Γ_{in} is measured.

C. Results of the Measurement

Fig. 12 shows the measured Γ_{in} circles corresponding to frequencies $2f_{LO}$ and $2f_{LO} \pm f_{if}$. The measured scattering parameters of network N are listed in Table III. The radius R_m is obtained directly from the measured Γ_{in} circle and R_c is obtained from calculation with (5).

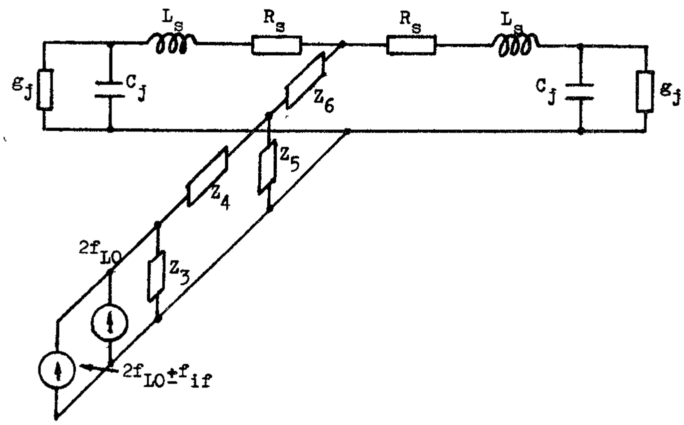

Fig. 13. The equivalent circuit for the analysis of the subharmonically pumped mixer.

TABLE III
MEASURED SCATTERING PARAMETERS

Para. / Fre.	S_{11}	S_{12}	S_{22}	R_m	R_c
$2f_{LO}$	$0.023\angle -90.5$	$0.254\angle 61.04$	$0.534\angle 51.0$	0.087	0.090
$2f_{LO}+f_{if}$	$0.328\angle -35.0$	$0.459\angle -46.3$	$0.415\angle 5.0$	0.262	0.254
$2f_{LO}-f_{if}$	$0.356\angle -95.5$	$0.412\angle -40.3$	$0.345\angle 4.2$	0.200	0.192

TABLE IV
EMBEDDING IMPEDANCES

Fre. / Impt.	f_{if}, f_{LO} $f_{LO} \pm f_{if}$	$2f_{LO}-f_{if}$	$2f_{LO}$	$2f_{LO}+f_{if}$	above $2f_{LO}+f_{if}$
Z_6(ohm)	50.0	$80.1\angle 69.7$	$195.3\angle -88.2$	$168.0\angle 76.7$	0.0
Z_5(ohm)	50.0	$169.2\angle -69.9$	$267.8\angle -79.7$	$157.4\angle 78.1$	0.0
Z_4(ohm)	50.0	$227.3\angle 11.3$	$154.2\angle 36.2$	$349.6\angle -27$	0.0

TABLE V
MEASURED AND COMPUTED RESULTS

Conversion Loss (DSB)	Measured Computed	6.35 (dB) 7.24 (dB)
LO Power	Measured Computed	13.50 (mW) 22.80 (mW)

Since R_s and L_s of the diode have been given, the parameters of network N_1 can be determined.

This method of measurement can also be used to measure the embedding network parameters at other LO harmonics and sideband frequencies. Moreover, it can also be used to measure the embedding network parameters of other microwave active circuits.

IV. Program and Computed Results

A special program has been developed for the nonlinear and linear analyses of the subharmonically pumped mixer. The nonlinear analysis is based on multi-reflection techniques [6]. The equivalent circuit for analysis is shown in Fig. 13. The impedances Z_4, Z_5, and Z_6 are obtained from the scattering parameters we have measured at $2f_{LO}$ and $2f_{LO} \pm f_{if}$. Z_3 is the source impedance. The embedding impedances at other LO harmonics and sideband frequencies are given. They are listed in Table IV. The computed results with an analysis program are listed in Table V and compared with measured results.

The discrepancy between the measured and computed results is caused by a) the error of measurement of conversion loss and embedding impedances and b) the error of the embedding impedances at other LO harmonics and sidebands which are given but not measured since the instruments are limited.

V. Conclusions

1) A *W*-band subharmonically pumped mixer has been developed with packaged Schottky diodes. The advantages of this mixer are its reliability and the convenience of installing and changing diodes.

2) A new method for measuring the embedding network parameters of the subharmonically pumped mixer has been developed and measurement has been carried out directly at *W*-band.

3) A special program for the analysis of the subharmonically pumped mixer has been developed and used for the computation of mixer performance from measured network parameters.

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