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THE INVESTIGATION OF W BAND MICROSTRIP INTEGRATED HIGH ORDER FREQUENCY MULTIPLIER BASED ON THE NONLINEAR MODEL OF AVALANCHE DIODE

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Abstract—A research of W band microstrip integrated high order frequency multiplier based on avalanche diode is presented. The associated nonlinear model of avalanche diode driven by external RF signals for high order frequency multiplication is presented and analyzed according to the physical property of avalanche diode. Subsequently the circuit of microstrip integrated high order multiplier is analyzed. In experiment, maximum output power of 6.5 mW with the efficiency of about 0.62% is obtained at output frequency of 94.5 GHz with 15th multiplication order. The phase noise of output 94.5 GHz signal is about −90.83 dBc/Hz and −95.67 dBc/Hz at 10 KHz and 100 KHz offset.

1. INTRODUCTION

High stable and low phase noise millimeter wave frequency source is the key factor for many millimeter and submillimeter wave applications. The development of millimeter wave system requires the circuits with low volume, high integration and stability. Millimeter wave oscillators, such as avalanche diode oscillator and Gunn oscillator, are the important way to generate millimeter signals [1–11]. But they are usually built with waveguide cavity structure, which have complex circuit tuning and is sophisticated and difficult in system integration. Subsequently, kinds of integrated oscillator based on avalanche diode are developed, which have relative high output power but poor phase noise and frequency stability due to the operation character of oscillation mode [12, 13].

Frequency multiplier is the effective way to obtain high stable and low phase noise millimeter wave signals. To people's interest, the rich high order harmonics character of avalanche diode with very low parasitic resistance in millimeter wave range render itself very suitable to achieve high order frequency multiplier in a single stage at millimeter wave band [14, 15]. Avalanche diode high order multiplier has achieved excellent performance from 30 GHz to 140 GHz and it has been successfully used in millimeter wave radar tansceiver and measurement equipments [16–18]. These initial high order frequency multiplier are all built with waveguide cavity structure similar to avalanche oscillator [19–22]. Then the high order frequency multiplier with microstrip-waveguide circuit structure is developed, which has simpler circuit structure [23]. But they all need careful and complex circuit tuning to obtain good performance.

This paper first introduces the physical property of avalanche diode and a nonlinear model of avalanche diode for high order frequency multiplication is presented and analyzed. Then the circuit analysis of the microstrip integrated multiplier is presented. In experiment good results have been obtained, which is consistent with the prediction of the nonlinear model analysis.

2. THE NONLINEAR MODEL OF AVALANCHE DIODE FOR HIGH ORDER FREQUENCY MULTIPLICATION

According to physical operation property of avalanche diode, it can be best analyzed by dividing the diode into three parts as shown in Fig. 1: (1) the narrow avalanche area, where the electric field is strong enough to cause carriers avalanche multiplication by impact ionization [14, 24, 25]; (2) the drift area, where no carriers are generated and carriers travel at their saturated velocities; (3) the inactive area which presents the undesirable parasitic resistance of avalanche diode [26].

During the avalanche breakdown process of avalanche diode, the generation and transportation of avalanche carriers conform to the continuity equations of semiconductor structure [27, 28]:

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + \alpha_n(E)\left|J_n(x,t)\right| + \alpha_p(E)\left|J_p(x,t)\right| \quad (1)$$

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + \alpha_n(E)\left|J_n(x,t)\right| + \alpha_p(E)\left|J_p(x,t)\right| \quad (2)$$

$$J_n(x,t) = qn(x,t)\,v_n \quad (3)$$

$$J_p(x,t) = qp(x,t)\,v_P \quad (4)$$

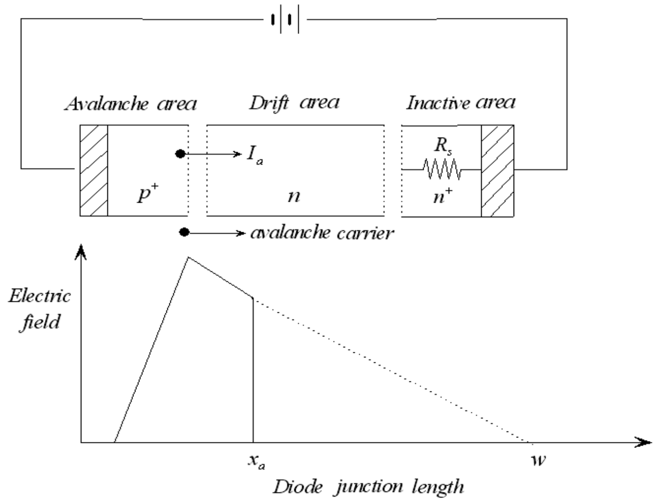


Figure 1. The model of avalanche diode structure.

where n and p are the densities of electrons and holes, J_n and J_p are the electron and hole current densities, α_n and α_p are the ionization rates of electron and hole, v_n and v_p are the electron and hole drift velocities, q is the electronic charge. Since the avalanche carriers are just generated in the narrow avalanche area, these parameters which are the function of space position x and time t are considered as having no space variation in the avalanche area and just changing with the time t. So avalanche current density J_a could be derived by adding (1) and (2) and integrating it over the length of avalanche area with considering the different ionization rates of electron and hole:

$$\frac{1}{(v_n+v_p)\,2}\frac{dJ_a}{dt}=J_a\frac{\int\limits_0^{x_a}\alpha_n(E)\left[\exp\left(\int\limits_0^{x}-(\alpha_n(E)-\alpha_p(E))\,dx'\right)\right]dx-1}{\int\limits_0^{x_a}\left[\exp\left(\int\limits_0^{x}-(\alpha_n(E)-\alpha_p(E))dx'\right)\right]dx}+\frac{J_s}{\int\limits_0^{x_a}\left[\exp\left(\int\limits_0^{x}-(\alpha_n(E)-\alpha_p(E))\,dx'\right)\right]dx} \tag{5}$$

where J_s is the thermally generated reverse saturation current density.

In high order frequency multiplication mode of avalanche diode, the optimized semiconductor structure of avalanche diode is based on $p^+ - n - n^+$ single drift structure with high punch through factor F, which is defined as $F = W/x_a$ shown in Fig. 1. So there are just the electron carriers to form avalanche current in the breakdown of avalanche diode with $p^+ - n - n^+$ structure and the generated avalanche current density J_a could be reduced from (5).

$$\frac{dJ_a}{dt} = \frac{2J_a}{\tau_a}\left(\int_0^{x_a} \alpha_n(E)\,dx - 1\right) + \frac{2J_s}{\tau_a} \tag{6}$$

where τ_a is the transit time of avalanche area. The high order harmonics character due to the fierce nonlinearity of avalanche current could be analyzed by considering the modulation function of external RF signals to the carrier ionization rate, which is given by:

$$\begin{aligned}\varphi(V_{RF}) &= \int_0^{x_a} \alpha_n(E)\,dx - 1 \cong \overline{\alpha_n(E)}x_a - 1\\ &= \overline{\alpha_n(E_c + E_{RF})}x_a - 1 = \overline{\alpha_n\left(E_c + \frac{V_{RF}}{x_a}\right)}x_a - 1\end{aligned} \tag{7}$$

Thus the modulation effect of external RF signals to the carrier ionization rate could be expressed by expanding $\varphi(V_{RF})$ by Taylor series and retaining terms up to the third order with enough accuracy.

$$\varphi(V_{RF}) = \alpha_n(E_c)\,x_a - 1 + \alpha_n'(E_c)\,V_{RF} + \frac{\alpha_n''(E_c)}{2x_a}V_{RF}^2 + \frac{\alpha_n'''(E_c)}{6x_a^2}V_{RF}^3 \tag{8}$$

The avalanche current generation character of avalanche diode driven by external RF signals with sufficient intensity could be analyzed by substituting (7) and (8) into (6), which is given by:

$$\begin{aligned}V_{RF} = &\frac{\tau_a}{2\alpha_n'(E_c)\,J_a}\frac{dJ_a}{dt} + \frac{J_s}{\alpha_n'(E_c)}\left[\frac{1}{J_s} - \frac{1}{J_a}\right]\\ &- \left[\frac{\alpha_n''(E_c)}{\alpha_n'(E_c)\,2x_a} + \frac{\alpha_n'''(E_c)}{\alpha_n'(E_c)\,6x_a^2}V_{RF}\right]V_{RF}^2 - \frac{\alpha_n(E_c)}{\alpha_n'(E_c)}x_a\end{aligned} \tag{9}$$

Meanwhile, the electron ionization rate $\alpha_n(E_c)$ is defined as:

$$\alpha_n(E_c) = A_n \exp\left(-\frac{b_n}{E_c}\right) \tag{10}$$

where A_n and b_n are the electron ionization rate constants. Thus (9) could be transformed into:

$$\begin{aligned} V_{RF} = & \frac{\tau_a}{2\alpha'_n(E_c)J_a}\frac{dJ_a}{dt} + \frac{J_s}{\alpha'_n(E_c)}\left[\frac{1}{J_s} - \frac{1}{J_a}\right] - \left[\frac{1}{2x_aE_c}\left(\frac{b_n}{E_c} - 2\right)\right. \\ & \left. + \frac{1}{6x_a^2E_c^2}\left(6 + b_n\left(\frac{b_n}{E_c^2} - \frac{4}{E_c} - 2\right)\right)V_{RF}\right]V_{RF}^2 - \frac{E_c^2}{b_n}x_a \end{aligned} \quad (11)$$

Equation (11) contains the relationship between the external RF voltage V_{RF} and avalanche current J_a. The terms on the right hand side of (11) can be interpreted as shown in references [29, 30]. Evidently, the first term presents the voltage across the nonlinear avalanche inductor which is given by:

$$L_a = \frac{\tau_a}{2\alpha'_n(E_c)J_a} \quad (12)$$

And the second term presents the voltage across a nonlinear resistor whose V-I relationship is given by:

$$V_R(J_a) = \frac{J_s}{\alpha'_n(E_c)}\left[\frac{1}{J_s} - \frac{1}{J_a}\right] \quad (13)$$

Finally, the third and fourth terms present a nonlinear voltage controlled voltage source which has following form:

$$\begin{aligned} V_n = & \left[\frac{1}{2x_aE_c}\left(\frac{b_n}{E_c} - 2\right)\right. \\ & \left. + \frac{1}{6x_a^2E_c^2}\left(6 + b_n\left(\frac{b_n}{E_c^2} - \frac{4}{E_c} - 2\right)\right)V_{RF}\right]V_{RF}^2 - \frac{E_c^2}{b_n}x_a \end{aligned} \quad (14)$$

Thus the narrow avalanche area, which generates avalanche current, could be modeled as the circuit structure of the three series nonlinear components parallel with the avalanche capacitance which are determined by semiconductor geometric structure and material.

$$C_a = \frac{\varepsilon A}{x_a} \quad (15)$$

where ε is the dielectric constant and A is the diode junction area. In drift area there is a spatial average effect for injected avalanche current J_a. Drift area could be model as the circuit structure of a short-time averager of avalanche current J_a parallel with the geometric capacitance of drift area, which is given by:

$$J_e = \frac{1}{\tau_d} \int_{t-\tau_d}^{t} J_a\left(t'\right) dt' \tag{16}$$

$$C_d = \frac{\varepsilon A}{(w - x_a)} \tag{17}$$

where τ_d is the transit time of drift area. So the nonlinear model of avalanche diode could be expressed by the equivalent circuit of avalanche area connected with the equivalent circuit of drift area and parasitic resistance R_s according to (9)–(17) as shown in Fig. 2.

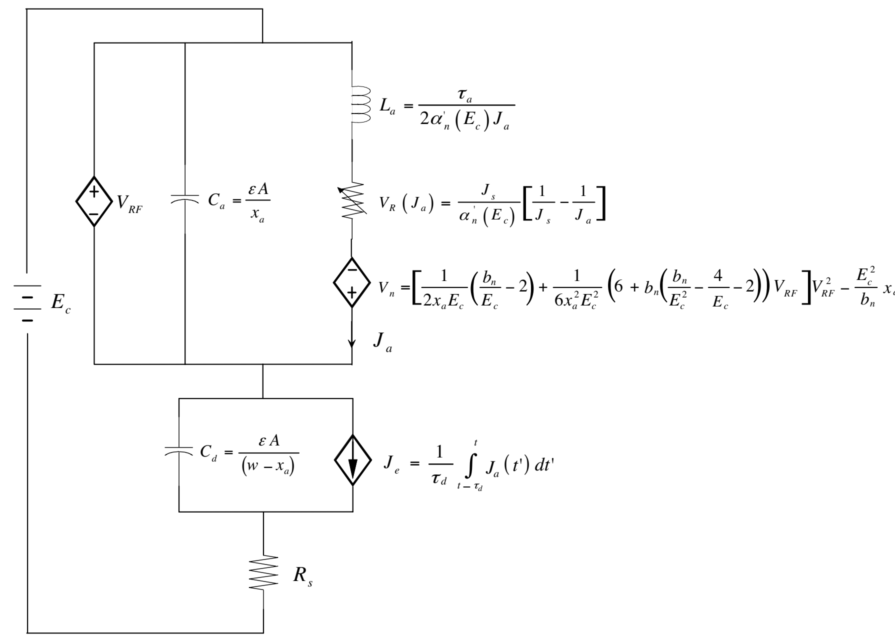
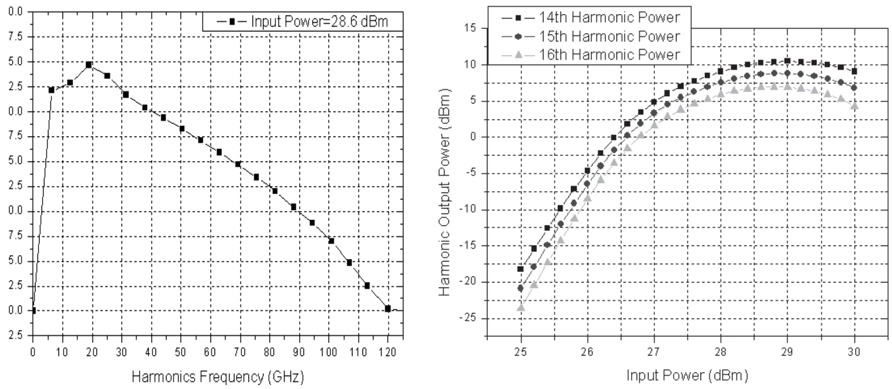


Figure 2. The nonlinear model of avalanche diode for frequency multiplication.

The nonlinear model of avalanche diode is consist of linear lumped elements, nonlinear lumped elements and nonlinear controlled sources, in which each element bears a simple relationship with the physical operation mechanism inside avalanche diode. As a result, these elements could be built in the ADS software for establishing the nonlinear model of avalanche diode to analyze the harmonics character by harmonic balance method. When the nonlinear model of avalanche



(a) (b)

Figure 3. The high order harmonics character of avalanche diode (a) the output harmonics character of avalanche diode (b) the 14th, 15th and 16th harmonics power of input 6.3 GHz RF signals.

diode is driven by the external input 6.3 GHz RF signals, the high order harmonics up to 110 GHz will generate with effective output power as shown in Fig. 3.

In Fig. 3, the high order harmonics character of avalanche diode has been predicted by the nonlinear model effectively. The simulated output harmonics power with 14th, 15th and 16th order indicate that avalanche diode is very suitable for the high order frequency multiplier in millimeter wave band.

3. THE CIRCUIT ANALYSIS OF MICROSTRIP INTEGRATED MULTIPLIER

Because of the different operation frequency range between input RF signals and output high order harmonic signals, the input and output circuit of microstrip integrated multiplier are built in two different substrates with thickness of 0.508 mm and 0.127 mm, relative dielectric constant of 3.2 and 2.2, which is benefit for them to realize good circuit match independently. Avalanche diode is connected to input and output circuit by gold tape. The equivalent circuit model of the microstrip integrated multiplier is shown in Fig. 4.

In the input RF circuit, avalanche diode is firstly connected to the 50 Ω microstrip line. A five stage high-low impedance low pass filter achieves the rejection of high order harmonics leaking into input circuit while passing the input RF signals with low insertion loss. The

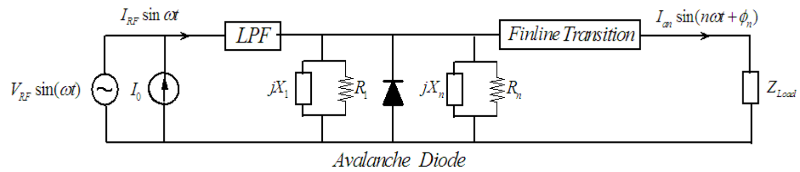


Figure 4. The circuit model of microstrip integrated high order multiplier.

constant current bias connection is made to avalanche diode through a high-low impedance filter connected to the $50\,\Omega$ microstrip line. The microstrip line is DC isolated from input RF signals connector by a block capacitor. The circuit and measured S parameter of input circuit are shown in Figs. 5(a) and (c). In the output millimeter wave circuit, avalanche diode is firstly connected to an impedance gradated microstrip line by gold tape. The output impedance matching

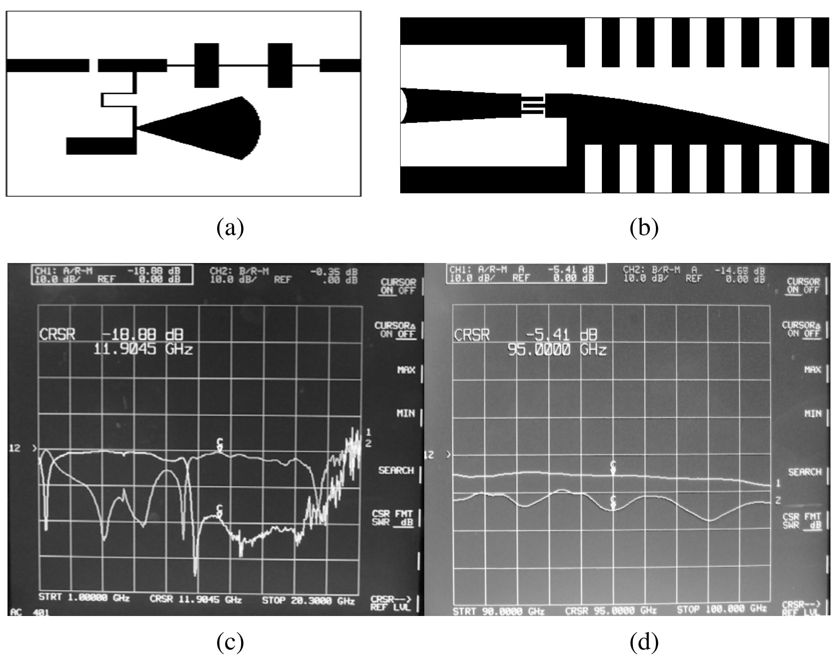


Figure 5. The input and output circuit and measured S parameter, (a) the input circuit, (b) the output circuit, (c) the measured S_{11} and S_{21} of input circuit, (d) the measured S_{11} and S_{21} of output circuit with back to back structure.

is completed by optimizing the width and length of gold tape and impedance gradated line. A three stage coupled lines achieve the DC isolation from the output finline transition. This DC block coupled line and finline transition is special optimized to pass the specific output high order harmonic at 94.5 GHz and reflect other harmonics energy back to avalanche diode for increasing output harmonic power. The output circuit and measured S parameters with back to back structure are shown in Figs. 5(b) and (d).

Subsequently, according to the nonlinear model analysis of avalanche diode for high order frequency multiplication, the simulation model of microstrip integrated multiplier could be built by importing the S parameters of input and output circuit into ADS software. The circuit schematic of the microstrip integrated multiplier and associated simulation results are shown in Fig. 6 and Fig. 7.

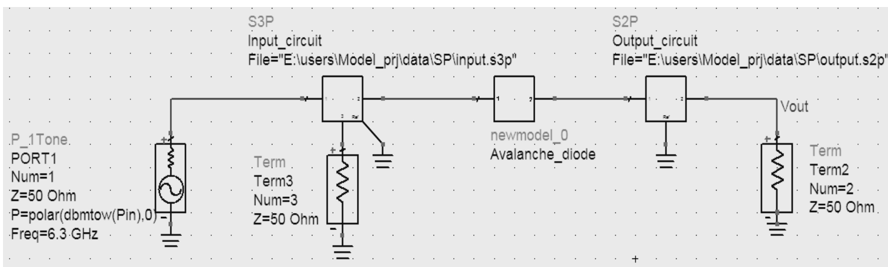


Figure 6. The simulation model of microstrip integrated high order multiplier.

As comparing with Fig. 3, the 15th harmonic power of input 6.3 GHz signal has been increased obviously with lower input RF power and the 14th and 16th harmonics power of input 6.3 GHz signal have been decreased largely, which demonstrate that the three stage DC block coupled line and microstrip to waveguide finline transition in the output circuit have reflected other harmonics back to avalanche diode effectively for increasing the 15th output harmonic power largely. The optimized circuit structure of microstrip integrated multiplier is very suitable for operating at the output frequency of 94.5 GHz with a narrow bandwidth.

4. EXPERIMENT RESULTS

The avalanche diode used in microstrip integrated multiplier is operated at 7–8 V and 60–110 mA. In experiment, the 15th frequency multiplication order is chosen and the output frequency is around

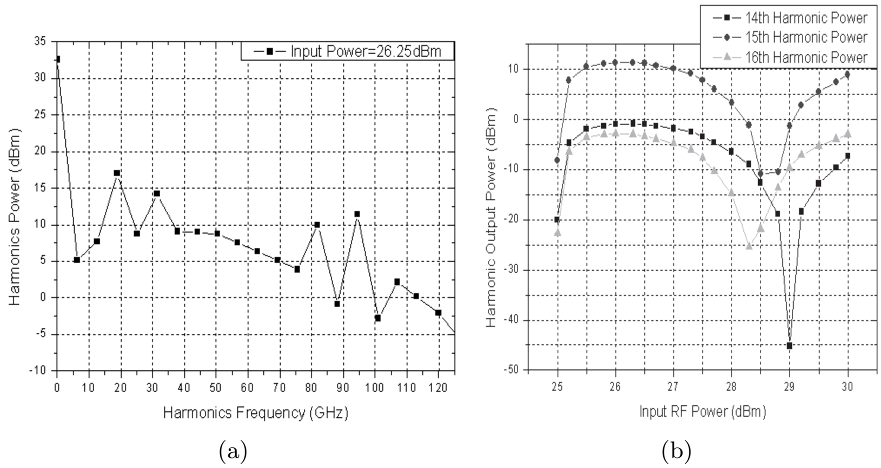


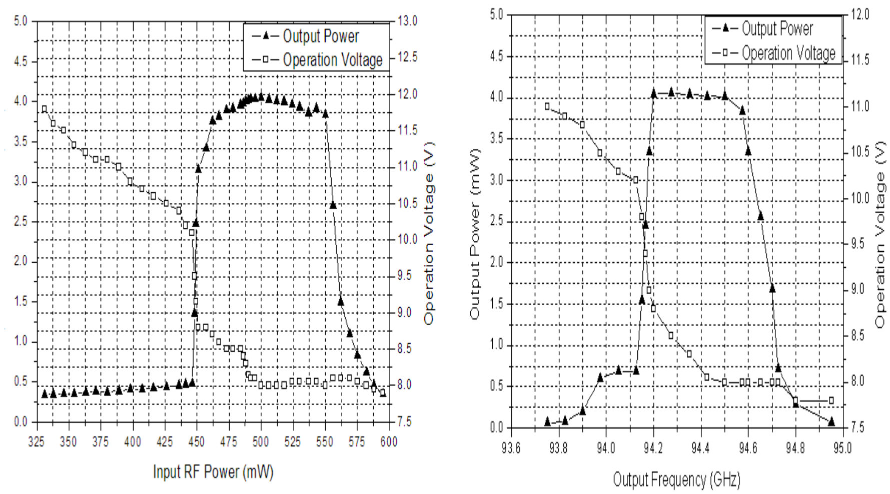
Figure 7. The high order harmonics character of microstrip integrated multiplier (a) the output harmonics character of the multiplier (b) the 14th, 15th and 16th harmonics power of input 6.3 GHz RF signals.

94.5 GHz while the input RF signal is around 6.3 GHz. The maximum output power measured from the microstrip integrated multiplier at output waveguide port is about 6.5 mW with 0.62% conversion efficiency at output frequency of 94.5 GHz operating at 8 V and 105 mA, which are close to the simulation value of 11.431 dBm of the output 15th harmonic power in microstrip integrated multiplier. Larger bias current could increase the output harmonic power but it also increase the instability of the avalanche diode. The undesirable parasitical oscillation of the avalanche diode will occur when the bias current is approaching to 110 mA. The stable and safe operation current is about from 70 to 100 mA, which could excite effective output harmonic power without parasitical oscillation. The measured relationship of the 15th output harmonic power between input RF power and output frequency operating at 80 mA are shown in Fig. 8.

In Fig. 8, the optimized input power to excite 15th high order harmonic power effectively is about from 450 mW to 550mW and about 450 MHz operation bandwidth has been achieved from 94.18 GHz to 94.63 GHz with output power larger than 3 mW. Good phase noise character of the 94.5 GHz output signals has been obtained and the phase noise formula of frequency multiplier could be expressed by:

$$L_{f_{out}} = L_{f_{in}} + 20 \log N + \Delta L_{add} \tag{18}$$

The measured phase noise character of the microstrip integrated



(a) (b)

Figure 8. The relationship of the 15th harmonic power between input RF power and output frequency, (a) with the input RF power, (b) with the output frequency.

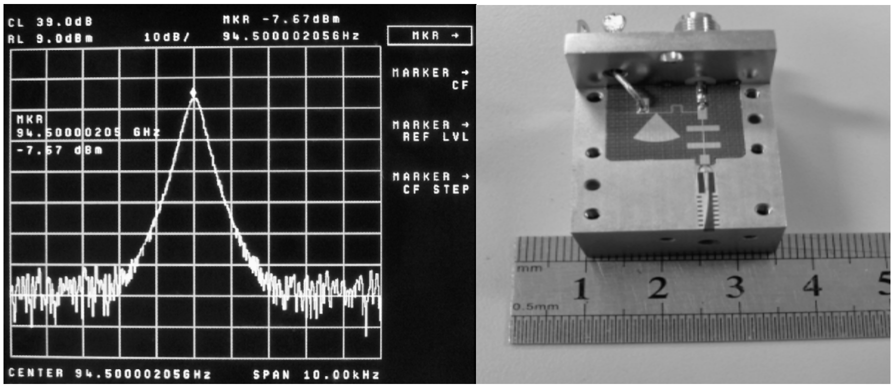
multiplier at the output frequency of 94.5 GHz with 15th multiplication order is shown in Table 1:

Considering the inaccuracy of measurement system, Table 1 has demonstrated that the phase noise of the microstrip integrated high order multiplier based on avalanche diode are very accord with the phase noise rule of frequency multiplier. Since the low phase noise and high stable RF signals could be obtained easily, the high quality millimeter wave signals are expected to provide by the high order

Table 1. The measured phase noise of the microstrip integrated multiplier.

Phase noise at 6.3 GHz	−113.33 dBc/Hz @10 KHz	−118.5 dBc/Hz @100 KHz	−108.83 dBc/Hz @3 KHz
Phase noise at 94.5 GHz	−90.83 dBc/Hz @10 KHz	−95.67 dBc/Hz @100 KHz	−85.17 dBc/Hz @3 KHz
20log15	23.5 dB	23.5 dB	23.5 dB
ΔL_{add}	−1 dB	−0.67 dB	0.16 dB

frequency multiplier of avalanche diode. The spectrum of output 94.5 GHz signal and the picture of microstrip integrated high order multiplier are shown in Fig. 9:



(a) (b)

Figure 9. (a) The spectrum of output 94.5 GHz signal, (b) the picture of the microstrip integrated high order multiplier.

5. CONCLUSION

A W band microstrip integrated high order frequency multiplier based on avalanche diode is presented. The nonlinear model of avalanche diode has predicted the high order harmonics character of avalanche diode driven by external RF signals with sufficient intensity effectively, which is utilized in the design of microstrip integrated multiplier. Good results have been achieved in experiment, which demonstrated that the microstrip integrated high order multiplier could provide high quality millimeter wave signals and has broaden application in millimeter wave systems.

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