Design of Ka-band antipodal finline mixer and detector*

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Abstract: This paper mainly discusses the analysis and design of a finline single-ended mixer and detector. In the circuit, for the purpose of eliminating high-order resonant modes and improving transition loss, metallic via holes are implemented along the mounting edge of the substrate embedded in the split-block of the WG-finline-microstrip transition. Meanwhile, a Ka band slow-wave and bandstop filter, which represents a reactive termination, is designed for the utilization of idle frequencies and operation frequencies energy. Full-wave analysis is carried out to optimize the input matching network of the mixer and the detector circuit using lumped elements to model the nonlinear diode. The exported S-matrix of the optimized circuit is used for conversion loss and voltage sensitivity analysis. The lowest measured conversion loss is 3.52 dB at 32.2 GHz; the conversion loss is flat and less than 5.68 dB in the frequency band of 29–34 GHz. The highest measured zero-bias voltage sensitivity is 1450 mV/mW at 38.6 GHz, and the sensitivity is better than 1000 mV/mW in the frequency band of 38–40 GHz.

Key words: conversion loss; voltage sensitivity; antipodal finline; harmonic balance analysis

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1. Introduction

The E-plane finline structure is successfully applied in many millimeter wave circuits and systems, which has the following advantages[1, 2]: it does not require a back short and can be integrated together with other planar circuits; it eliminates the requirement for designing a complicated IF/DC return path. The conventional application range of the finline circuit technology covers the frequencies between 10 and 100 GHz[2]. Recently, the finline structure has been extended to the THz region[3, 4].

In our designed circuit of a finline mixer and detector, the metallic via hole technique is used in the mounted substrate of the WG-finline-microstrip transition to eliminate high-order modes, which not only lowers the conversion loss but also reinforces the reliability of the circuit by increasing the mounting groove depth. Meanwhile, a Ka-band slow-wave and bandstop filter is designed to act as a short circuit for idle frequencies and the operation frequencies utilization, which can effectively lower the conversion loss and improve the voltage sensitivity by forming a reactive termination for them. This is because the performance of the mixer is strongly dependent on the nature of the reactive load (short, open, capacitive, or inductive)[5]. This technique is also very useful for detectors. Full-wave analysis is carried out to optimize the input matching network of the mixer and the detector using lumped elements to model the diode. The exported S-matrix of the optimized circuit is used for conversion loss and voltage sensitivity analysis. Experimental results show that the conversion loss of the mixer is flat and less than 5.68 dB in the frequency band of 29–34 GHz. For the detector, the measured zero-bias voltage sensitivity is better than 1000 mV/mW in the frequency band of 38–40 GHz.

2. WG-finline-microstrip transition

Since the advent of the finline structure, many methods have been used to lower the WG-finline-microstrip transition loss, such as an early open ended mounting groove, a short ended mounting groove in split-block and a serration form in a mounted substrate circuit[6]. In this paper, a metallic via hole is introduced to lower the transition loss and to increase the mounting groove depth for reinforcing the reliability of the mounted soft circuit. The function to describe the finline taper contour is given by

$$W(z) = (b + w)/2 \times \sin^2(\pi z/2L), \quad (1)$$

where b is the height of the WR-28 waveguide, w is the output microstrip width, and L is the finline taper length. A mode transducer in the form of a semicircle is used to complete the transition, which is designed so that any resonance is shifted to a frequency outside the operation band[7]. The transition structure is presented in Fig. 1, and the dimension parameters are given as follows: b = 3.56 mm, w = 0.76 mm, L = 12 mm, and w_1 = 0–1.6 mm. Following reports found in research papers about the recently developed substrate integrated waveguide (SIW) technology, we can also use a metallic via hole array to approximately model the PEC boundary[8, 9] to eliminate the

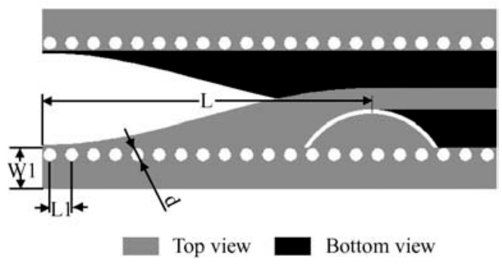

Fig. 1. Configuration of the WG-finline-microstrip transition.

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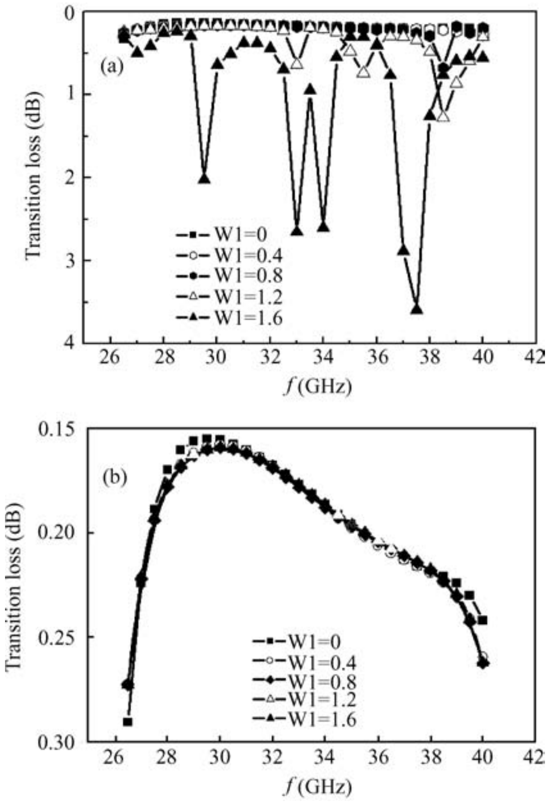

Fig. 2. Simulated WG-finline-microstrip transition loss: (a) Without metallic via hole; (b) With metallic via hole.

effect of the mounting groove. The parameter d and L_1 are determined to be 0.5 mm and 0.8 mm, respectively[8].

The substrate is an Arlon Diclad 880 with a thickness of 0.254 mm and a relative dielectric constant of 2.2. Figure 2 shows the simulated S-parameters both with a metallic via hole and without a metallic via hole under the condition of a varying parameter w_1. From Fig. 2(a), it can be found that when the parameter w_1 is wider than 0.8 mm, the transition loss caused by high-order modes begins to appear. With a further increase of w_1, the resonant effect of the high-order modes becomes more severe. Fortunately, while metallic via holes are implemented along the edge of the substrate, it can be found from Fig. 2(b) that the simulated transition loss stays almost unchanged for the same varying parameter w_1. Apparently, the high-order modes due to the mounting grooves are completely suppressed by the metallic via holes. Furthermore, the mounting reliability of the circuit can be reinforced with an increased mounting groove depth. The transition using a metallic via holes will be applied in our designed Ka-band mixer and detector.

3. Circuit architecture of the mixer and detector

The block diagram of the single-ended mixer is shown in Fig. 3. It consists of a WG-finline-microstrip transition, an input matching network, as well as a Ka-band slow-wave and bandstop filter. The transition parameters are the same as mentioned above except for parameter w_1, which is fixed at 1.6 mm to increase the circuit reliability and ease its mounting. The GaAs flip-chip SBD DMK2790 from Skyworks Inc is

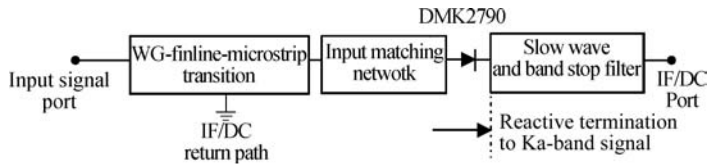

Fig. 3. Circuit block diagram of the mixer.

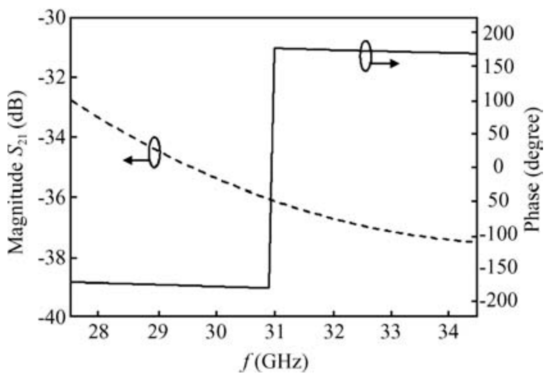

Fig. 4. Simulated S-parameter and reflection phase of the filter.

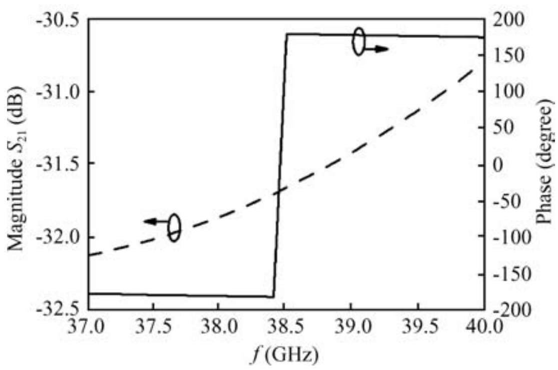

Fig. 5. Simulated S-parameter and reflection phase of the filter.

used, and the basic SPICE parameters are: $R_s = 7\ \Omega$, $n = 1.05$, $C_{jo} = 0.05$ pF, $I_S = 0.5$ pA, $V_j = 0.82$ V, $m = 0.26$[10].

In the mixer, a reactive termination for the RF/LO and $2f_{LO} - f_{RF}$ signals is formed by a Ka-band slow-wave and bandstop filter. This filter also serves as a low pass filter (LPF) for IF signal. It is shown in Fig. 4 that the simulated transmission loss is lower than 31 dB in the frequency range of 27.5–34.5 GHz; the reflection phase deviation from both 180° and –180° is less than –8.3° in the frequency range of 31 to 34.5 GHz and 9.1° from 28.5 to 30.9 GHz, respectively. This filter presents approximately a short circuit to the above mentioned idle frequency $2f_{LO} - f_{RF}$ and the operation frequencies in the range of 29–34 GHz. For the idle frequency signals $f_{LO} + f_{RF}$ and $2f_{LO} + f_{RF}$, other bandstop filters can be designed, turning the reflection phase of the bandstop filters by a phase shift network[7, 11], to present an optimum reflection phase to them. In order to simplify the circuit structure and save simulation time, less consideration is given to them in the mixer circuit.

The circuit block diagram and the split-block of the detector are the same in the case of the mixer. Figure 5 shows that the simulated transmission loss of the slow-wave and bandstop filter is lower than 30.6 dB in the frequency band of 37–40 GHz; the reflection phase deviation from –180° and 180° is less than 8.1° from 37 to 38.4 GHz and –4.9° from 38.6 to

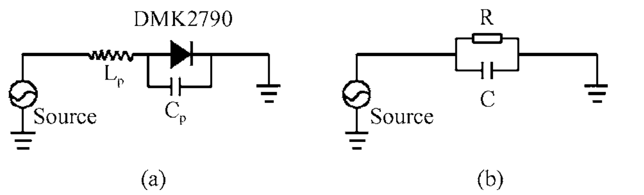

Fig. 6. Input impedance: (a) Calculation model of the diode, including parasitic parallel capacitance and series inductance; (b) Equivalent circuit model.

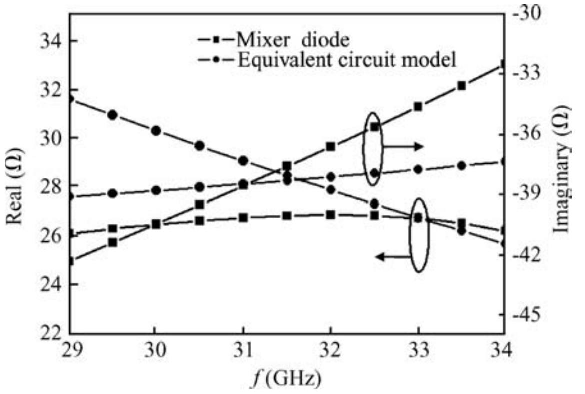

Fig. 7. Simulated input impedance of the mixer diode and the equivalent circuit model.

40 GHz. This filter presents an equivalent short circuit to RF frequency in the range of 37–40 GHz.

4. Equivalent circuit model

The simplified equivalent circuit model of the nonlinear diode is shown in Fig. 6. One terminal is shorted by our designed Ka-band slow-wave and bandstop filter, as shown in Fig. 6(a), which includes a parasitic series inductance (L_P = 0.1 nH) and a parallel capacitance (C_P = 0.02 pF). These values of the parasitic parameters are determined by our previous experience. At 31.5 GHz, the calculated input impedance of the diode is Z_{in} = 28.5 − j38.2 (Ω) with an LO power of 10 dBm. At this power level, the mixer diode can be adequately pumped. It is shown that a pumped single mixer diode can be modeled as a resistor of 50 to 150 Ω in parallel with a capacitor between C_{jo} to $1.5C_{jo}$[12]. Based on the calculated input impedance of the shorted diode, the diode can be simply modeled as a capacitance (C = 0.085 pF) in parallel with a resistor (R = 80 Ω) as depicted in Fig. 6(b). The real and imaginary part of the input impedance is presented in Fig. 7 from 29 to 34 GHz, which presents a good agreement between the mixer diode and its equivalent circuit model.

The whole mixer circuit structure is analyzed by using CST software with lumped elements to model the diode. The input matching network is specially optimized with the goal of a low input return loss. The S-parameters of the optimized mixer circuit obtained from the CST simulations are exported for HBA analysis in ADS. The simulated conversion loss is shown in Fig. 9. It can be found that the simulated conversion loss is lower than 6.5 dB in the frequency band of 28.5–34.5 GHz.

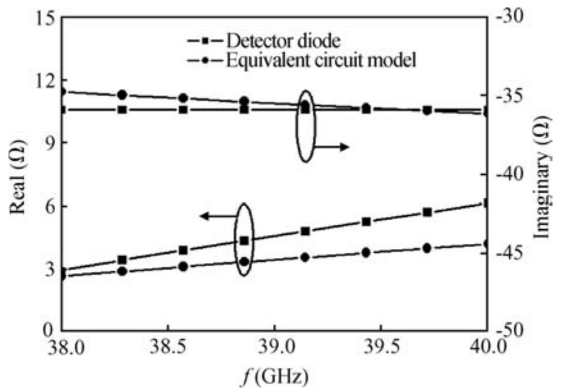

Fig. 8. Simulated input impedance of the detector diode and the equivalent circuit model.

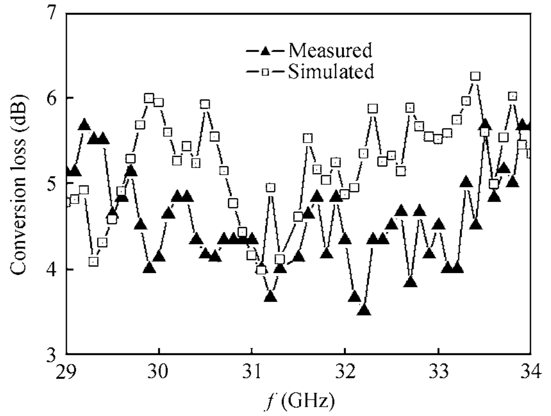

Fig. 9. Measured and simulated conversion loss of the mixer.

For the detector diode, the input power of the detector is kept at –20 dBm, which insures that the diode is operating in the square-law region. When one terminal of the diode DMK2790 is shorted at 39 GHz, the calculated input impedance of the diode is Z_{in} = 3.6 − j34 (Ω). In this case, the diode is modeled as a resistor R = 160 Ω in parallel with a capacitance C = 0.085 pF. Figure 8 shows, in the frequency band of 29–34 GHz, the real and imaginary parts of the input impedance to the detector diode and its equivalent circuit model, which are in good agreement. Using the same simulation method as for the mixer, the simulated voltage sensitivity is shown in Fig. 11.

5. Experimental results

In the measurement setup, the LO frequency is provided by a Gunn oscillator with a fixed frequency of 31.40 GHz, and the optimum LO power of 7.9 dBm to pump the mixer diode. The RF is provided by a HP83572C signal generator with a fixed power of –8.65 dBm. The output IF signals of the mixer are measured by an Agilent 8356EC spectrum analyzer. The measured conversion loss result is also plotted in Fig. 9. The measured conversion loss is flat and less than 5.68 dB from 29 to 34 GHz; the lowest tested conversion loss is 3.52 dB at 32.2 GHz. The photograph of the designed mixer is shown in Fig. 10.

As shown in Fig. 11, for the detector operating in the frequency band of 38–40 GHz, the measured zero-bias voltage

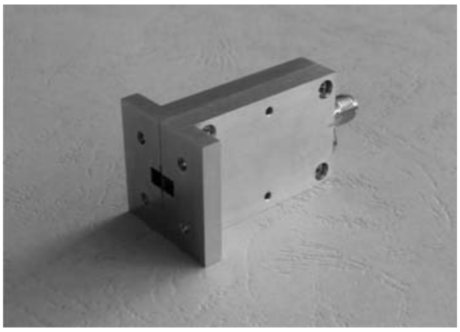

Fig. 10. Photograph of the mixer.

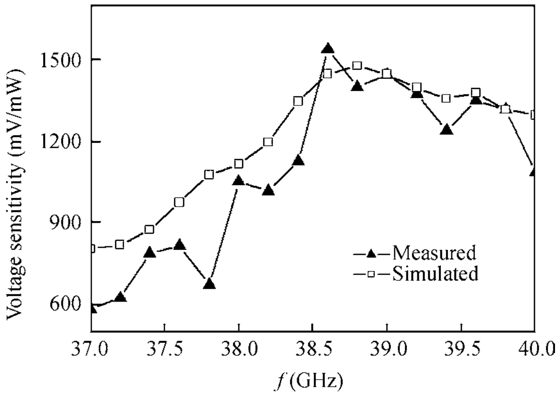

Fig. 11. Measured and simulated voltage sensitivity at an input RF power of –20 dBm.

sensitivity is better than 1000 mV/mW, and the highest voltage sensitivity is 1450 mV/mW at 38.6 GHz.

6. Conclusion

This paper describes the analysis and design of an E-plane finline single-ended mixer and detector in the Ka-band. In the circuit, the metallic via holes are introduced to eliminate high-order modes, which are generated in the mounting groove, and the reliability of the circuit is increased by widening the mounting groove. Meanwhile, a Ka-band slow-wave and bandstop filter is used as a reactive termination to idle frequencies and operation frequencies, which can effectively lower the conversion loss of the mixer and improve the voltage sensitivity of the detector. The nonlinear diode is modeled with its equivalent circuit for the optimization of the input matching network by using CST software. Experimental results show that the conversion loss of the mixer is as low as 3.52 dB at 32.2 GHz; the conversion loss is less than 5.68 dB in the frequency band of 29–34 GHz. For the detector, the measured zero-bias voltage sensitivity is better than 1000 mV/mW in the frequency band of 38–40 GHz. The highest voltage sensitivity is 1450 mV/mW at 39 GHz. The circuit structure is simple and easy to be realized, and it can be extended to be applied to submillimeter waves.

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