Low Conversion-Loss Fourth Subharmonic Mixers Incorporating CMRC for Millimeter-Wave Applications

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***Abstract*—Low conversion-loss millimeter-wave fourth subharmonic (SH) mixer designs are proposed in this paper. A millimeter-wave (35 GHz) fourth SH mixers with four open/shorted stubs is designed and measured. The conversion loss is less than 15 dB within a 2.4-GHz bandwidth. The minimum loss is 11.5 dB at the center frequency. By replacing two of the shunt stubs with a dual-frequency in-line stub consisting of newly developed compact microstrip resonating cells (CMRCs), the performance of the SH mixer is improved significantly. At 35 GHz, the conversion loss of this new fourth SH mixer is as low as 6.1 dB with a 3-dB bandwidth of 6 GHz. The conversion loss in the whole Ka-band (26.5–40 GHz) is less than 16 dB. The proposed fourth SH mixer incorporating with CMRCs provides a low-cost high-performance solution for RF subsystem design.**

***Index Terms*—Compact microstrip resonating cell (CMRC), microstrip line mixer, quasi-lumped component, subharmonic (SH) mixer.**

I. Introduction

SUBHARMONIC (SH) mixers employing an antiparallel diode pair have been demonstrated to have very good performance in microwave and millimeter wave [1]–[9]. A generic rule, for the optimal design of SH mixers, was proposed by Madjar [8]. A second SH mixer using a coplanar waveguide with only 10-dB conversion loss was introduced in [9]. One would expect that the use of a fourth SH mixer should further reduce the cost and improve the isolation between the RF and local oscillator (LO) signals. However, design of the fourth SH mixer with a low conversion loss remains a great challenge [10], [11].

The most important part in the design of an SH mixer is to provide suitable terminations at both ends of an antiparallel diode pair for RF, LO, IF, and idler signals. An open/shorted-stub fourth SH mixer, as an extension of the open/shorted-stub second SH mixer, is presented in this paper. The stubs provide return paths for the RF, LO, and IF signals and grounded terminations for an important idler frequency. The performance of the SH mixer can be improved by providing reactive terminations with suitable phases at both ends of the diode pair for more idler frequencies. This is implemented in this paper by replacing two of the stubs in the mixer by two compact microstrip resonating cell (CMRC) structures. The CMRC is a microstrip structure with slow-wave and stopband effects.

Microstrip transmission lines incorporating an electromagnetic bandgap (EBG) structure exhibit bandstop and slow-wave characteristics, which can be exploited to reject unwanted frequency and to reduce dimensions of the microstrip structure. The EBG structure can be in the form of a periodic array of dielectric inclusions with a dielectric constant different from that of the host dielectric substrate [12] or a two-dimensional periodic array of perforations in the ground plane of the microstrip line [13]. In the study of a microstrip transmission line over a periodically perforated ground plane, it is found that the propagation constant strongly depends on the orientation and location of the transmission line with respect to the two principal axes of the periodic perforations [14]. As the ground plane is perforated, the substrate must be suspended so that the circuits cannot be fixed on a metal base for mechanic robustness. Perforation on the transmission line itself [15], [16] is a potential solution to these problems. The authors proposed two one-dimensional microstrip EBG cells, which exhibit remarkable slow-wave and bandstop characteristics even when one single cell is used [17]. Other than being a nonperiodic structure, the unit cell possesses two important features of the EBG structure, namely, slow wave and bandstop. This structure is alternatively called a CMRC [18].

There has been much literature reporting applications on EBG structures in microstrip antennas, filters, resonators, power amplifiers, and mixers [18]–[23]. The unique characteristics of a CMRC make it particularly useful in microwave and millimeter-wave circuit design [18], [23]. Due to its small size, a CMRC can be embedded in circuits as a lumped component, even though it has a distributive structure. By incorporating this novel quasi-lumped component in microwave and millimeter-wave circuits, not only can we reduce their size, but also dramatically improve their performance. In this paper, we have applied the CMRC in the design of fourth SH mixers. By properly selecting the bandgap region and location of the CMRC, two of the four open/shorted stubs in the fourth SH mixer can be replaced by a dual-frequency stub consisting of two CMRCs. Due to the unique bandstop and quasi-lumped characteristics of the CMRC, the proposed CMRC fourth SH mixer can easily be built with good performance.

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II. Design of Open/Shorted-Stub Fourth SH Mixers

The open/shorted-stub second SH mixers are introduced in [9] and [24]. For the fourth open/shorted-stub SH mixer, the stubs should not only provide all the return paths for the RF, LO, and IF signals, but also present suitable reactive terminations for the idler frequencies: $f_{\rm idle} = |f_{\rm RF} \pm 2nf_{\rm LO}|$, where $n = 1, 3, 4, 5 \ldots$, especially the two fundamental idler frequencies high idler $f_{\rm RF} + 2f_{\rm LO}$ and low idler $f_{\rm RF} - 2f_{\rm LO}$. As an extension of the second SH mixer, we propose an open/shorted-stub fourth SH mixer. The mixer, as shown in Fig. 1, consists of four open/shorted stubs (A, B, C, and D) at the two terminals of the antiparallel Schottky diode pair with RF and LO signals applied from left- and right-hand-side terminals of the diode pair, respectively. Two of the four stubs are tilted to increase the distance between adjacent stubs to reduce mutual coupling between them. The IF signal is taken out from the RF port. The dc/IF block at the RF arm and the low-pass filter (RF choke) at the IF arm are used to prevent these two from leaking on each other. On the left-hand side of the diode pair, there are two open stubs A and B. Stub A has a length of a quarter-wavelength of the LO signal. When the LO signal is applied from the right-hand side of the diode pair, it grounds the LO signal on the left-hand side of the diodes, providing the LO signal with a return path. The RF frequency is approximately four times that of the LO. Hence, Stub A is about one wavelength of the RF signal and appears as an open circuit to the RF signal at the left-hand-side end of the diode pair without reflecting the RF signal coming from the left-hand side. Stub B is half the wavelength of the RF signal and also appears as an open circuit to the RF signal at the left-hand-side end of the diode pair. However, it is a shorted terminal for one of the most important idler frequency in the mixer, i.e., $f_{\rm RF} - 2f_{\rm LO}$. Since $f_{\rm RF} \approx 4f_{\rm LO}$, this idler frequency is approximately one-half of the RF signal. Stub B is a quarter-wavelength open stub at this idler frequency, providing a short circuit.

On the right-hand side of the diode pair, there is a shorted stub (Stub C) and an open stub (Stub D). Stub D is a quarter-wavelength open stub, providing a shorted terminal on the right-hand side of the diodes for the return path of the RF signal applying to the diode pair from the left-hand side. It is approximately 1/16 wavelength at the LO frequency and its effect on the LO can be neglected. Stub C is a quarter-wavelength shorted stub at the LO frequency appearing as an open circuit on the left-hand side of the diodes at the LO frequency. However, it is a half-wavelength shorted stub for the idler frequency $f_{\rm RF} - 2f_{\rm LO}$. Thus, this idler frequency is also short terminated on the right-hand side of the diodes. Stub C provides an IF return path on the right-hand side of the diode pair. Stub C also provides a return path for RF because it is a shorted stub at RF frequency. However, with Stub D, the operating bandwidth is enhanced. The diode pair is Alpha Industry's DMK2308. Its parameters are given in Table I.

The LO and IF ports are subminiature A (SMA) coaxial connected. The RF port is a W-28 rectangular waveguide. The RF signal is transferred from the waveguide to the microstrip by means of a waveguide–finline–microstrip transition. It introduces an insertion loss of approximately 0.5 dB. The proposed fourth SH mixer operates as follows. The RF signal feeds from the left-hand side of the diode pair by the waveguide–finline–microstrip transition and returns through Stub D. Stub A and B on the left-hand side have no effect on the RF signal. The LO signal is fed from the right-hand side of the diode pair and returns through Stub A on the left-hand side of the diode pair. Stub D has very little and Stub C has no effect on the LO signal. Stubs B and C provide shorted terminals for idler frequency $f_{\rm RF} - 2f_{\rm LO}$ on the left- and right-hand sides of the diode pair, respectively. Hence, the idler frequency is suppressed and conversion loss is improved.

The circuit in Fig. 1 was simulated using *Microwave Office*.[1] Table II shows the simulated conversion loss and device impedances for LO, RF, and IF. Fig. 2 shows the measured conversion loss of the fourth SH mixer described above operating at 35 GHz. Within approximately 2 GHz of 3-dB bandwidth, the conversion loss is less than 14 dB with the lowest point

TABLE I
Alpha Industry DMK2308 Diode Parameters

$C_{j0}(pF)$	$C_p(pF)$	$I_s(A)$	$R_S(\Omega)$	n	$\phi_{bi}(V)$	$f_C(GHz)$
0.05	0.02	5×10^{-13}	7.0	1.05	0.82	455

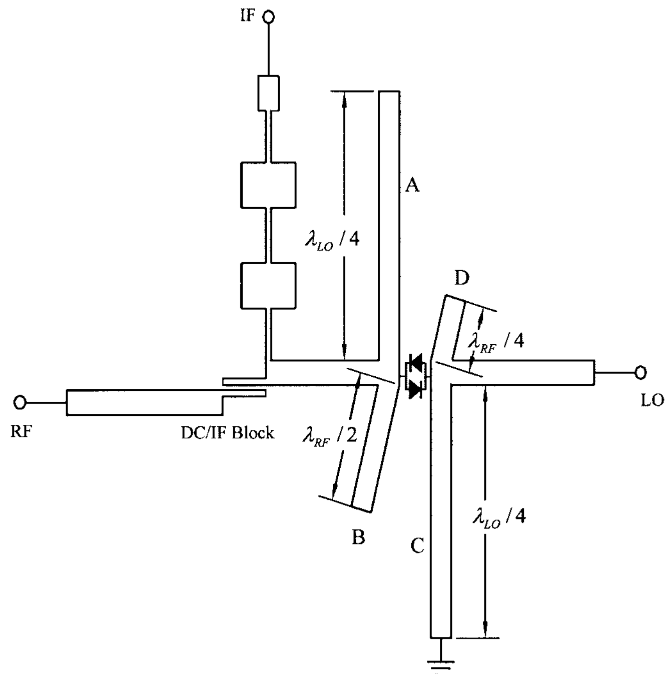

Fig. 1. Proposed open/short-stub fourth SH mixer.

TABLE II
Simulation Results of the Open/Short-Stub Fourth SH Mixer With $f_{\rm LO} = 8.5$ GHz, $f_{\rm RF} = 35$ GHz, and $f_{\rm IF} = 1$ GHz

P_{LO} (dBm)	Conversion Loss (dB)	$Z_{LO}(\Omega)$	$Z_{RF}(\Omega)$	$Z_{IF}(\Omega)$
7	10.8	48.7-j42.7	12.5-j1.1	73.7+j7.0
9	10.4	36.3-j28.7	10.3+j5.7	53.2+j7.7
11	10.5	28.2-j20.5	8.8+j8.7	43.8+j7.0

[1]*Microwave Office* is a trademark of Applied Wave Research Inc., El Segundo, CA.

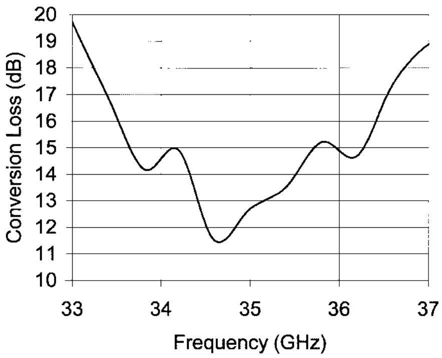

Fig. 2. Measured conversion loss of a 35-GHz open/short stub fourth SH mixer.

at 11 dB with a 0.5-dB insertion loss of the 35-GHz waveguide–finline–microstrip transition deducted from the conversion loss curve shown in Fig. 2. The IF frequency is fixed at 1.0 GHz. It can be seen that the open/shorted-stub fourth SH mixer is simple in structure and is easy to design with good performance.

III. Principle of the CMRC In-Line Stub Fourth SH Mixers

Although the open/shorted-stub fourth SH mixer introduced in Section II gives a good performance, there is still large room for improvement. In the above mixer, only one idler frequency, i.e., $f_{\rm RF} - 2f_{\rm LO}$, is suppressed by grounding on both sides of the diode pair which does not satisfied Madjar's rule [8] that termination of the idler frequency should have an optimized phase to minimize the conversion loss. The mixer does not provide a reactive termination for another important idler frequency, say, $f_{\rm RF} + 2f_{\rm LO}$, which can cause an increase in the conversion loss. The open stub, i.e., Stub D, on the right-hand side introduces a shunt reactance of approximately $-j80\,\Omega$ for the LO, causing an increase of the LO port voltage standing-wave ratio (VSWR). We try to resolve the above problems by employing CMRC in-line stubs.

A. Concept of In-Line Stub

An in-line stub is illustrated in Fig. 3. Signals f_1 and f_2 with $f_2 > f_1$ are fed into the input port of a microstrip line with a CMRC. The CMRC stopband and passband are located at f_2 and f_1, respectively. f_1 will pass through the CMRC to the output port with a small transmission loss, while f_2 will be reflected back to the input port with a small return loss. The reflection phase of f_2 can be tuned by changing the length between the CMRC cell and input port. The CMRC units with different stopband frequency locations can be cascaded in a descending frequency order to obtain a multifrequency reflection in-line stub.

B. Design of CMRC Using Distributive Equivalent Circuit

A lumped equivalent circuit for the CRMC has been introduced in [17]. This equivalent circuit explains why the slow wave and bandstop occurs in the CMRC and helps to investigate new perforation patterns for the CMRC. Its component values have no direct relationship with the physical structure, hence,

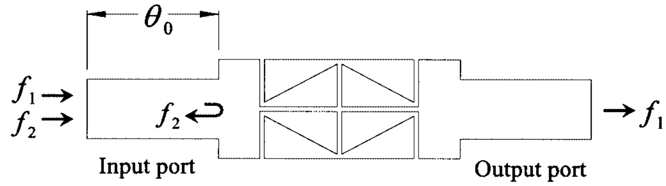

Fig. 3. CMRC in-line stub.

it makes circuit synthesis impossible for the CMRC. However, this can be done with the help of a distributive equivalent circuit. Fig. 4 shows the CMRC structure and its distributive equivalent circuit. It can be seen that all the components of the distributive equivalent circuit can be obtained directly from the original structure, and all the components are standard microstrip components, which can be calculated with satisfactory accuracy by closed-form equations [23]. To predict the performance of the CMRC accurately, some parameter modifications are necessary for the distributive equivalent circuit. The modifications include the following.

1) The microstrip step from the 50-Ω line to the narrow inductance line is a microstrip step from w_3 instead of w_4 to w_1. This is because the width on the other part of the 50-Ω line is occupied by the microstrip gap structures.
2) The length of microstrip taper line is the average length of the two sides of the triangle.
3) The length of the longitudinal narrow line is not $(a_3 - a_1)/2$, but $(a_2 - a_1)/2$ because of the microstrip gap's extension.
4) The width of the microstrip gap is not $(w_4 - w_2)/2$, but reduced by a factor of α. This is because one side of the gap is not a rectangular line, but a triangular line, which reduces the coupling capacitance area.

Fig. 4(b) shows a distributive equivalent circuit for the CMRC, as shown in Fig. 4(a). The parameters in Fig. 4(a) for the equivalent circuits are $a_1 = 0.2$ mm, $a_2 = 23.6$ mm, $a_3 = 24.0$ mm, $w_1 = 0.2$ mm, $w_2 = 0.6$ mm, $w_3 = 3.8$ mm, and $w_4 = 4.2$ mm. The substrate is Duroid 5870 with a dielectric constant of 2.95 and a thickness of 1.524 mm. Fig. 5 shows the S-parameters of the CMRC calculated using the distributive circuit. Also shown in Fig. 5 are the measured S-parameters of the CMRC. It can be seen that the distributive equivalent circuit can accurately simulate the performance of the CMRC. With the help of the distributive equivalent circuit, we can easily synthesize and optimize the CMRC by closed-form computer-aided design (CAD) equations. In contrast, many other EBG structures still need rigorous numerical simulation and a trial-and-error procedure is needed for the design. Due to perforation, the impedance of CMRC is larger than that of a normal microstrip line. Therefore, the CMRC section should be wider than that of a 50-Ω microstrip line, whose width can also be determined by an equivalent circuit.

C. Structure of CMRC In-Line Stub Fourth SH Mixer

The proposed CMRC in-line stub fourth SH mixer is shown in Fig. 6. It can be seen that the left-hand-side part of the CMRC fourth SH mixer is the same as that of the open/shorted stub fourth SH mixer. On the other hand, a dual frequency in-line

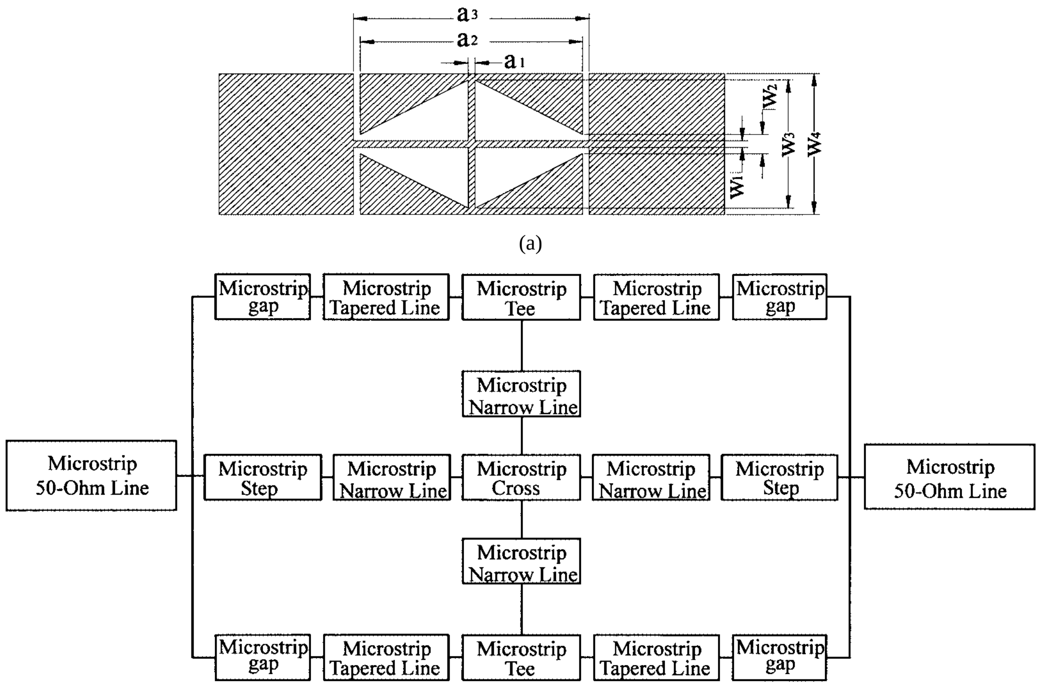

Fig. 4. CMRC structure. (a) Physical configuration. (b) Distributive equivalent circuit.

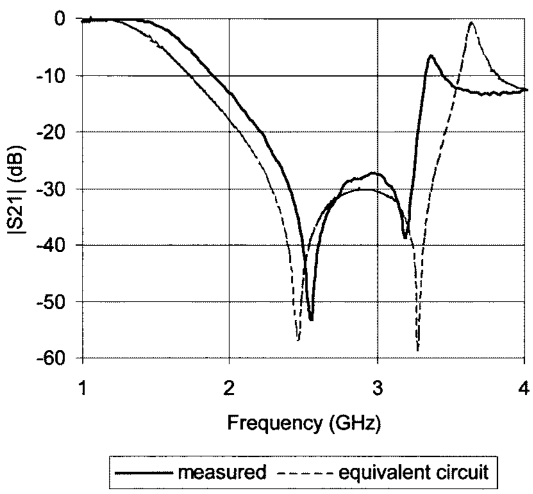

Fig. 5. Comparison of $|S21|$ obtained by measurement and the distributive equivalent circuit.

stub consisting of two cascading CMRCs replaces the open and shorted stubs on the right-hand side of the diode pair. The first CMRC on the right-hand side of the diode pair, i.e., CMRC-1, is a wide-band bandstop structure. Its stopband covers not only the whole RF band, but also the idler frequency $f_{\rm RF}+2f_{\rm LO}$. By tuning the length of L_1, CMRC-1 presents a short circuit on the right-hand side of the diode pair at the RF frequency providing the RF with the return path. CMRC-1 also appears as a reactive terminal for $f_{\rm RF}+2f_{\rm LO}$ leading to this idler suppression. Below the RF band, CMRC-1 can be taken as a section of a regular transmission line with a small insertion loss. The LO signal and idler frequency $f_{\rm RF}-2f_{\rm LO}$ can go through this CMRC section without being affected. The stopband of CMRC-2 is designed to be at the other idler frequency $f_{\rm RF}-2f_{\rm LO}$. By tuning the length of L_0, CMRC-2 provides a reflection with tunable phase

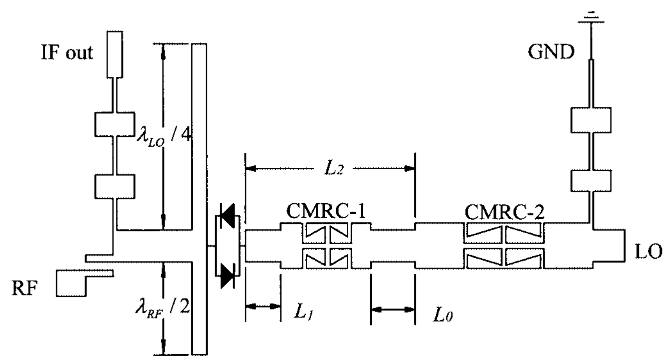

Fig. 6. CMRC in-line stub fourth SH mixer.

for $f_{\rm RF}-2f_{\rm LO}$ so that optimization can be conducted according to Madjar's rule [8]. There are two low-pass filters on the left- and right-hand sides of the diode pair, respectively. The left-hand-side low-pass filter is for taking out the IF signal, while the right-hand-side one is grounded for the IF return path.

IV. Design and Testing of a 35-GHz CMRC Fourth SH Mixer

A 35-GHz CMRC fourth SH mixer was built. The frequency at 35 GHz is an atmospheric window in the Ka-band. Many millimeter-wave communications and radar systems choose 35 GHz as the center frequency. The design of the 35-GHz LO is a principal challenge for down-converters in these systems. Dielectric-resonator stabilization, multiloop phase locked-loop (PLL), and frequency multiplier are common approaches for a good quality 35-GHz LO, but at the cost of a more complicated and expensive construction. The proposed fourth SH mixer in this paper needs only an 8.5-GHz LO, which can easily be realized with high performance using the PLL technique.

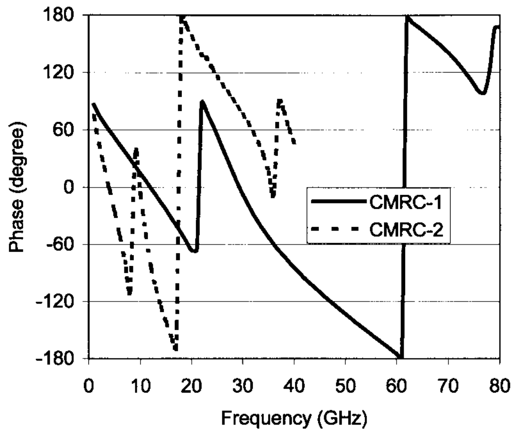

Fig. 7. Simulated reflecting phase of CMRC-1 and CMRC-2 in the fourth CMRC SH mixer.

A. Building of the 35-GHz CMRC Fourth SH Mixer

The SH mixer was built on a Duroid 5880 with $\varepsilon_r = 2.2$, $h = 0.254$ mm according to the structure in Fig. 6. In this circuit, the left-hand side of the diode pair consists of general microstrip structures, such as open stubs, high/low-impedance low-pass filter, coupling lines for dc block, etc. Following the usual procedure, they can be easily designed. The distributive equivalent-circuit model can be used for the initial design of the CRMC structures. Numerical simulation tools (such as *Ensemble 6.0*)[2] should be used for fine tuning. In most cases, equivalent-circuit results are accurate enough.

CMRC-1 in the mixer was designed to have a wide stopband for the RF frequency (35 GHz) and the higher fundamental idler frequency (70 GHz). Fig. 7 shows the phase of S_{11} of CMRC-1. At 35 GHz, the phase of S_{11} is $-53°$. To provide a short termination for 35 GHz, it should be $-180°$. Thus, a section of microstrip line with a roundtrip phase delay of $127°$ should be inserted between CMRC-1 and the diode. At 70 GHz, the phase of S_{11} is $140°$. However, the combination of CMRC-1 and the microstrip line at this frequency result in a $-114°$ reflection at the diode pair with a magnitude close to one.

Also shown in Fig. 7 is the reflecting phase of CMRC-2. CMRC-2 was designed to present a phase tunable reflection at the diode pair for the low fundamental idler frequency (17.5 GHz), while it introduces no insertion loss for the LO signal. By tuning the length of L_0, different reflection phase θ can be observed at the diode pair. The circuit in Fig. 6 was simulated using *Microwave Office*. Table III shows the simulated conversion loss and device impedances for LO, RF, and IF.

B. Measurement

Fig. 8 shows the circuit pattern of the CMRC fourth SH mixer. It is a little bit larger than the open/shorted-stub fourth SH mixer, as shown in Fig. 1, by 23% longer length and 16% narrower size. The LO and IF are fed in and taken out by SMA coaxial connectors. The RF signal is fed in through a standard WR-28 rectangular waveguide for the Ka-band. A finline–microstrip transition is employed to couple the RF signal from the waveguide to the microstrip line. The diode pair is also Alpha Industry's DMK2308. Three circuits with a different θ value are fabricated and measured. Fig. 9 shows the measured conversion loss. The measurement was done with the IF frequency fixed at 1.0 GHz. It can be seen that when $\theta = 130°$, the conversion loss is the lowest among these three designs. With 11-dBm optimum LO power, the lowest conversion loss of the mixer is 6.1 dB. The 3-dB bandwidth of the conversion loss is over 6.0 GHz. The conversion loss in the whole Ka-band (26.5–40 GHz) is less than 16 dB. Once again, a 0.5-dB insertion loss from the waveguide–finline–microstrip transition is deducted from the conversion loss curve shown in Fig. 9.

[2]*ENSEMBLE* is a trademark of Ansoft Inc., Pittsburgh, PA.

TABLE III
SIMULATION RESULTS OF THE CMRC IN-LINE STUB FOURTH SH MIXER WITH $f_{LO} = 8.5$ GHz, $f_{RF} = 35$ GHz, AND $f_{IF} = 1$ GHz

P_{LO} *(dBm)*	*Conversion Loss (dB)*	Z_{LO} (Ω)	Z_{RF} (Ω)	Z_{IF} (Ω)
5	6.9	63.4-j51.1	13.1-j1.4	83.6+j40.0
7	6.1	46.7-j26.5	15.8+j3.7	69.2+j39.0
9	7.4	35.3-j14.0	16.0+j3.3	60.9+j40.3

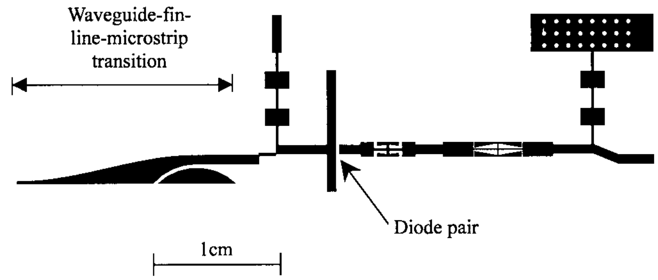

Fig. 8. Circuit pattern of the designed 35-GHz CMRC fourth SH mixer.

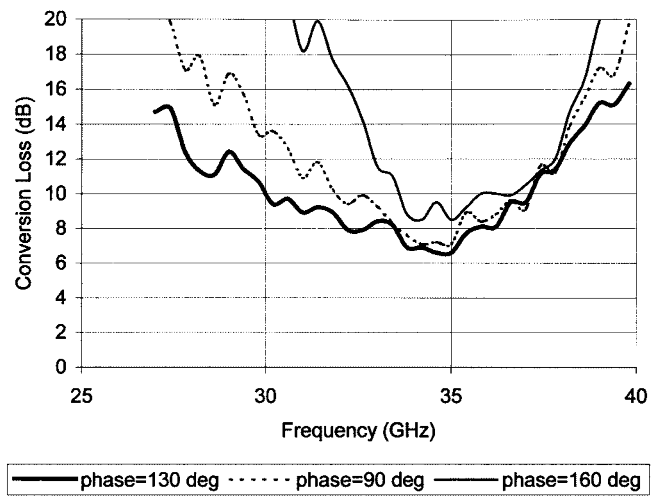

Fig. 9. Measured conversion loss of the CMRC SH mixers with different reflection phase θ for the lower idler frequency $f_{RF} - 2f_{LO}$. The LO power is 11 dBm for the optimal conversion loss.

V. CONCLUSIONS

As an extension of the second SH mixer, the proposed open/shorted-stub fourth SH mixer has good performance. It provides a grounded termination for the lower fundamental idler frequency, but not for the higher fundamental idler frequency.

Furthermore, the phase cannot be tuned. By replacing two of the stubs with a dual-frequency CMRC in-line stubs that can be optimized through individually tuning the reflection phase for different frequencies, the performance of the SH mixer has been significantly improved. A distributive equivalent circuit of the CRMC is proposed for the synthesis of the CMRC. Final designs have been verified with rigorous commercial software such as *Ensemble*. A 35-GHz CMRC in-line fourth SH mixer has been designed, fabricated, and measured. This mixer achieves a very low conversion loss of 6.1 dB. The 3-dB bandwidth of conversion loss is over 6.0 GHz. The conversion loss in the whole Ka-band (26.5–40 GHz) is less than 16 dB. This result even outperforms some fundamentally pumped mixer designs.

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