Wide-Band MMIC Kowari Mixer/Phase Shifters

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***Abstract*—A series of wide-band image-reject monolithic-microwave integrated-circuit mixer/phase shifters were designed, fabricated, and tested for operation in the microwave and millimeter-wave bands. Mixers based on diode and resistive-high electron-mobility transistor (HEMT) nonlinear elements are presented and compared in this paper. The diode-based Kowari (we christened our modified "rat-race" mixer "Kowari" after the common name of the small and somewhat rat-like carnivorous brush-tailed marsupial mouse, Dasyuroides byrnei, which inhabits the arid regions of central Australia) mixers have a bandwidth of approximately 45%, with up- and down-conversion loss [RF to/from IF (in this paper, we use "IF," "LO," and "RF" to label the ports associated with particular signals, not necessarily to describe the nature of the signals themselves)] less than 10 dB and up-conversion output power greater than 0 dBm. At band center, the down-conversion loss is approximately 7 dB. The novel resistive-HEMT-based Kowari mixers have a measured IF-to-RF up-conversion loss of approximately 2 dB and LO-to-RF conversion loss of approximately 13 dB over 17–25.5 GHz. While both circuit types realize wide-band 360° phase shifters when appropriate control voltages are applied, the resistive-HEMT-based Kowari has better linearity and a smaller insertion loss.**

***Index Terms*—Diode, GaAs, HEMT, mixer, MMIC.**

I. Introduction

MIXERS play a vital role in microwave and millimeter-wave radio systems as down-converters and, for architectures utilizing linear modulation schemes such as quadrature amplitude modulation (QAM), as up-converters. In signal-processing applications, phase shifters can be a useful system building block. While narrow-band circuits are quite suitable for radio products focused on a particular spectrum band, wide-bandwidth operation results in flexibility, economies of scale, and improved inventory costs.

The mixer/phase-shifter monolithic microwave integrated circuits (MMICs) described in this paper are based on a modified rat-race structure that utilizes a Lange coupler with two shorted ports to replace the three-quarter-wavelength delay line [1]. This reduces the size of the mixer and increases its bandwidth. Two ports of the rat race are used to apply the local oscillator (LO) and RF and the other two for connection of the nonlinear elements to ground. For the realization of this nonlinear element, we have explored the use of diodes fabricated with Schottky and high electron-mobility transistor (HEMT) MMIC processes and compared resulting circuit performance with that based on the use of HEMTs operating in their resistive mode.

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II. Circuit Description

In the diode cases, a single IF connection is made via a low-pass filter to the ring with capacitors isolating the Lange couplers and preventing the IF from shorting to ground, and capacitors at the LO and RF inputs to stop leakage of the IF signal down these paths. The use of these capacitors is an essential addition to the hybrid-structure suggested in [1] to allow it to be used in a mixer. The IF filter is realized with a series-L shunt-C series-L shunt-C topology with values chosen to present an open-circuit to LO and RF signals within the rat-race. The diodes are connected with opposing polarity so that a pump voltage shorts alternatively each arm of the rat race to ground as it biases one diode on while simultaneously turning the other diode off and opening the other arm for transmission. In the mixer mode, the LO provides the pumping action. In the phase-shifting mode, a phase-control voltage applied through the IF filter dominates the phase-shifted signal in magnitude and controls the diodes. Fig. 1(a) illustrates this circuit topology.

In a resistive-HEMT mixer, the HEMT drain is biased at $V\mathrm{ds} = 0$ V, while the HEMT gate is pumped to modulate the drain–source resistance and provide mixing action [2]. In our implementation, an IF (or phase-control) connection is made to each of the gates via a shunt-C series-L shunt-C low-pass filter and the rat race is connected to the drain. IF signals are applied in antiphase to ensure that one HEMT turns on as the other turns off, thereby shorting one arm of the rat race then the other. As the IF is applied to the transistor gate, and not the drain, the Lange-coupler-isolation capacitors used in the diode-based design are removed and the low-frequency drain voltage is held at 0 V via this path to ground. Moderate drain voltages do not modulate the drain–source resistance and, hence, the IF provides the pumping action for both up-conversion and phase-shifter operation. Use of the three-terminal device, with its inherent isolation of the controlling voltage (gate) from the controlled terminal (drain), as the control element in our circuit improves up-converter and phase-shifter performance. However, this structure, illustrated in Fig. 1(b), cannot be used as a down converter.

Two of these modified rat-race structures ("half-Kowaris"), either using diodes or resistive HEMTs as the nonlinear element, are combined with an on-chip Lange coupler and an on-chip Wilkinson power divider to produce an image-reject diode-based Kowari (d-Kowari) or resistive-HEMT Kowari

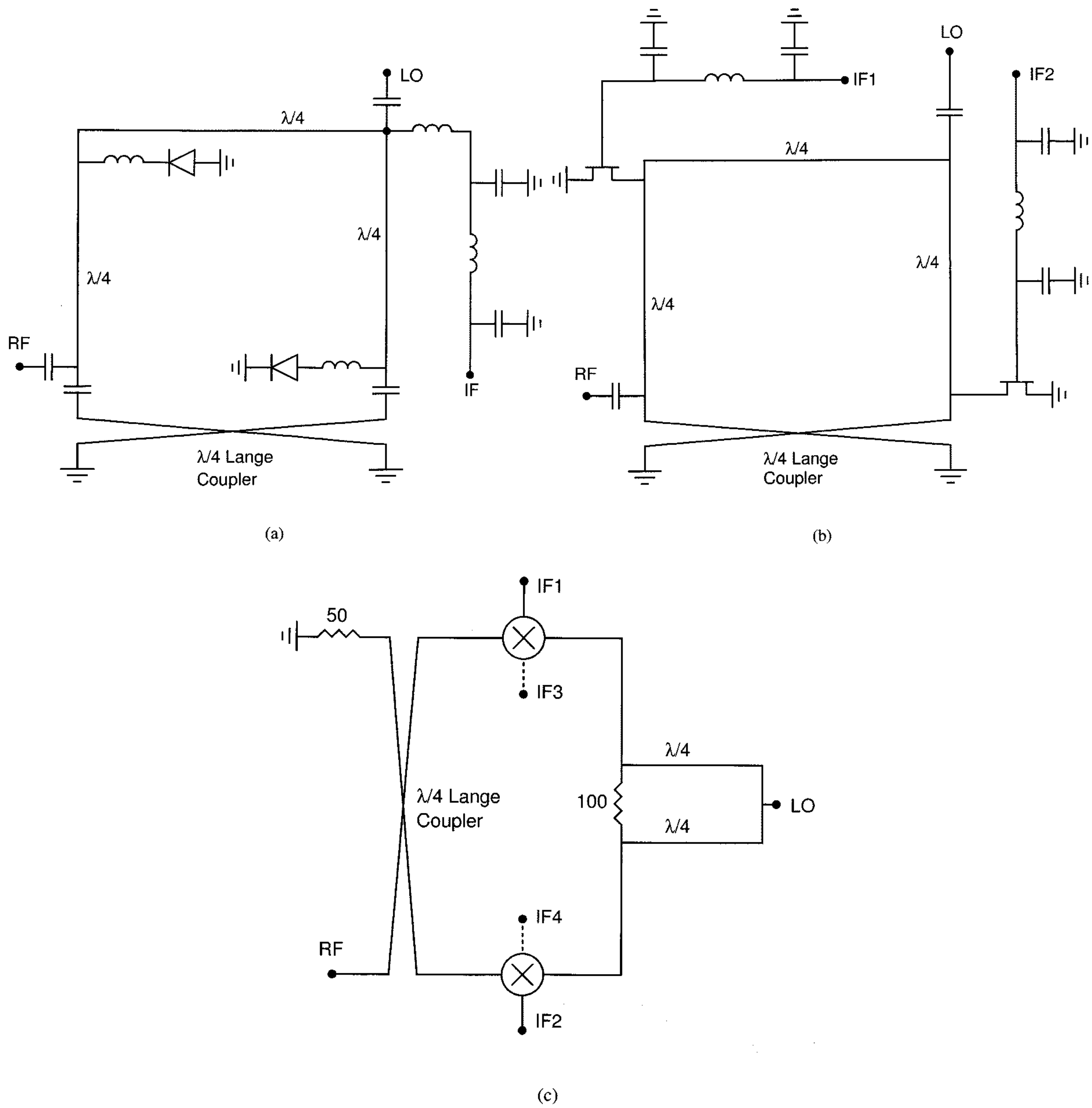


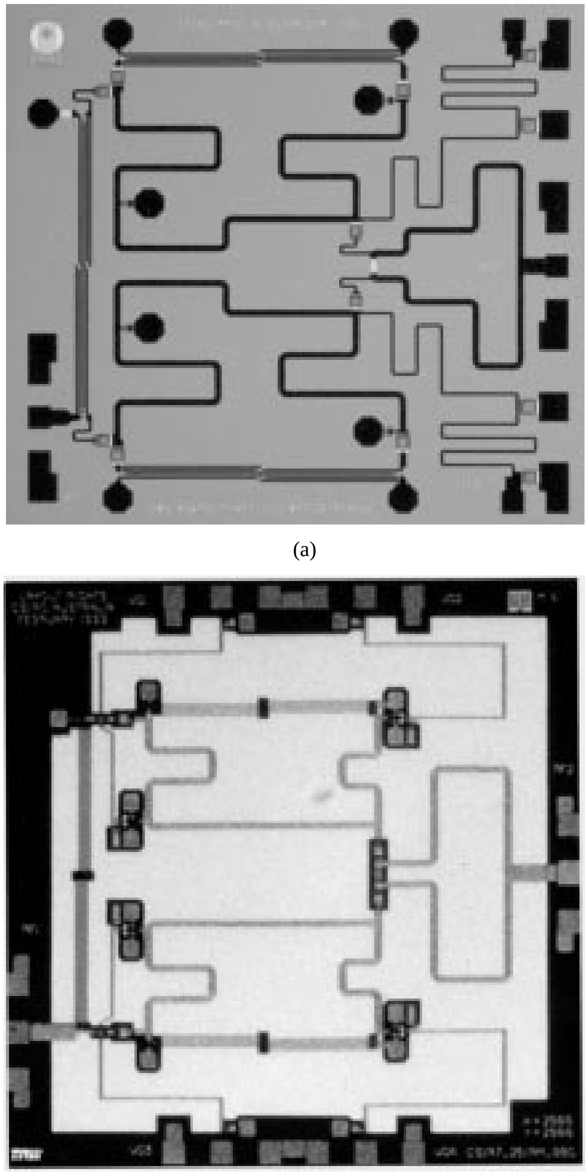
Fig. 1. Circuit diagrams showing lumped elements and quarter-wave Lange couplers and impedance transformers. (a) Half d-Kowari. (b) Half rH-Kowari. (c) Complete Kowari of either type (nodes IF3 and IF4 only exist in the rH-Kowari).

(rH-Kowari) architecture, respectively. The complete circuit topology is shown in Fig. 1(c).

The circuit parameters of the half-Kowaris and Wilkinson power-divider dimensions were initially set by hand calculation. The parameters and the layout (which is tied to the schematic by custom auto-layout "ael" code) were fine tuned by optimization with Libra. For the half-Kowaris, the diodes and HEMT elements can be modeled as nonlinear elements and nonlinear optimization employed to maximize circuit performance as a mixer. Alternatively, these elements can be modeled as linear elements in off and on states and the linear transmission and isolation properties of the half-Kowaris optimized. Both methods were used for the d-Kowari circuits and similar circuit dimensions were obtained. The latter was the prime design method for the rH-Kowari due to the lack of an accurate nonlinear model for the HEMT in the resistive operating region.

The d-Kowari has two IF ports that may be received in quadrature to produce a down-converting image-reject mixer, driven in quadrature to produce an up-converting single-side-band mixer or driven by dc or baseband I and Q channels to produce a phase shifter (vector modulator) or an m-phase-shift keying (m-PSK) direct modulator. We have reported some preliminarily d-Kowari results in [3]. The rH-Kowari has four IF ports: I and Q, and their inverses $\overline{I}$ and $\overline{Q}$, which driven with IF or control signals produce an up-converting mixer, phase shifter, or an m-PSK direct modulator.

A series of mixer/phase-shifter MMICs centered at 20, 25, 30, 40, and 60 GHz have been fabricated and tested using the Commonwealth Scientific and Industrial Research Organization (CSIRO), Epping, N.S.W., Australia, Schottky-diode process and the TRW 0.25-μm low-noise HEMT and 0.15-μm power HEMT processes. The HEMT processes were used to



(a)

(b)

Fig. 2. Circuit photographs. (a) 20-GHz d-Kowari MMIC fabricated at the CSIRO using their Schottky-diode process. (b) 25-GHz rH-Kowari MMIC fabricated at TRW using their 0.15-μm HEMT process.

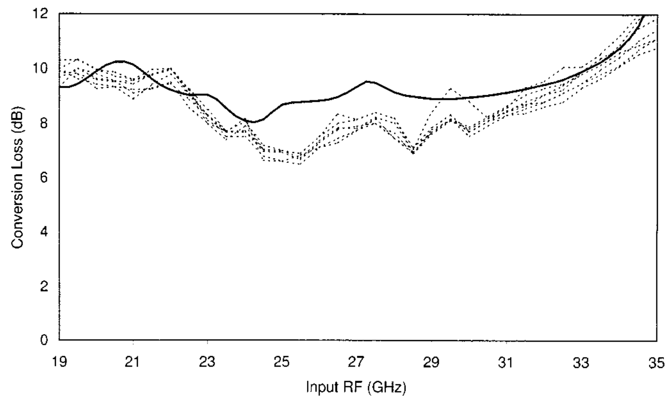


Fig. 3. Measured upper sideband RF-to-IF down-conversion loss for seven d-Kowaris (dotted lines) with a nominal center frequency of 25 GHz. Libra simulation is also shown (solid line).

create both d-Kowari and rH-Kowari mixer/phase shifters. For d-Kowaris fabricated with the four-finger 40-μm-wide diodes available in the TRW HEMT processes, we found inclusion of a small inductance in series with the diode improved circuit performance. The rH-Kowaris were fabricated using the four-finger 120-μm-wide HEMTs from the 0.15-μm TRW process. The substrate thickness for all three processes was 100 μm.

Fig. 2(a) shows a d-Kowari MMIC with 20-GHz center frequency fabricated at the CSIRO. The circuit size could be smaller than 2.6 $\times$ 2.4 mm, as here it is constrained by wafer dicing requirements and the size of other circuits on the wafer. This d-Kowari circuit has four ports: RF1 connected to the Lange coupler, RF2 connected to the Wilkinson coupler, and IF ports IF1 and IF2. The RF and LO can be connected to either ports RF1 or RF2 with similar performance due to rat-race symmetry. The low-pass IF filter allows the mixer to be used for IF up to about 5 GHz for direct up- or down-conversion by connecting I and Q baseband signals to the IF1 and IF2 ports, if desired. It can also be used as a 360° phase shifter by the application of appropriate control signals to the IF ports. Fig. 2(b) shows an rH-Kowari MMIC with 25-GHz center frequency fabricated at TRW. Its dimensions are 2.5 $\times$ 2.5 mm and, in this layout, the IF/phase-shift-control pads were labeled VG1, ..., VG4 instead of IF1, ..., IF4, as in Fig. 1(c).

III. Circuit Description

A. *d-Kowari Topology*

Fig. 3 shows the measured and simulated RF-to-IF mixer down-conversion loss of a 25-GHz center frequency d-Kowari fabricated using TRW's 0.15-μm power-HEMT process. The measurements were taken on seven circuits with a 15-dBm LO signal and an RF signal 1.5 GHz above the LO. The "conversion loss better than 10 dB" bandwidth of the mixer is approximately 45% and there is good agreement between Libra simulation and measurement. The measured image rejection also exceeds 20 dB over this band. In IF-to-RF up-conversion, the measured "better than 10 dB" bandwidth of this mixer is also at least 45% with good agreement between simulation and measurement. Other measurements on these circuits indicate an LO isolation (i.e., unconverted LO signal leaking out of the RF port) of at least 20 dB over the band with up to 35-dB isolation near the band center.

Measurements taken on 20, 30, 40, and 60 GHz d-Kowari fabricated using the TRW HEMT processes give very similar values to those already quoted, as do circuits fabricated using the CSIRO Schottky-diode process. For example, the 20-GHz d-Kowari in Fig. 2(a), which was fabricated at the CSIRO using the latter process, has a measured RF-to-IF down-conversion loss of 9 dB, an image rejection greater than 15 dB, and LO isolation of approximately 30 dB when pumped with a 12-dBm LO. The 40-GHz d-Kowari has a measured RF-to-IF down-conversion loss of 7–8 dB over a wide band, and at 38.5 GHz, a measured IF-to-RF up-conversion loss of 6.5 dB, an input-referred 1-dB compression-point of 11 dBm, and has an LO isolation of approximately 20 dB.

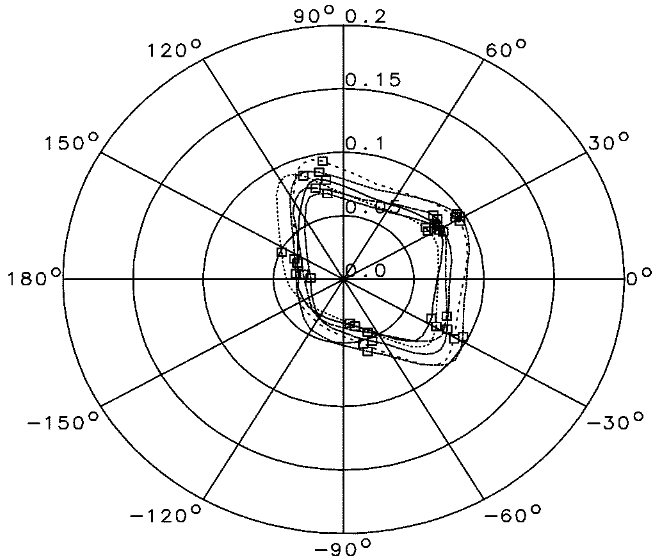


Fig. 4. Measured LO-to-RF transmission coefficient (i.e., S_{21}) loci of six d-Kowari at 24 GHz as θ is slowly varied using the auxiliary output from the HP8510 to drive a sine and cosine generator.

The Kowari's usefulness as a phase shifter (vector modulator) is determined by applying $\sin(\theta)$ and $\cos(\theta)$ waveforms to the IF1 and IF2 ports and measuring the circuit's LO-to-RF transmission parameter (i.e., S_{21}) as a function of θ. Ideally, a polar plot of $S_{21}(\theta)$ should be a unit circle centered at the origin. Squareness of the locus is caused by nonlinearity in each of the quadrature mixers. The center offset is the vector sum of the LO leakage through each mixer, and this worsens the loss variation with angle.

Fig. 4 shows the loci of S_{21} for six d-Kowari phase shifters similar to that described above as θ is slowly varied from 0° to 360°. The loci enclose the origin ensuring that all phases can be generated by appropriate control signals; however, there is significant loss variation with θ. There is high LO-to-RF insertion (conversion) loss of between 20–32 dB, which is primarily due to the nonideal behavior of the diode impedance, and further worsened by the center-offset effect. Similar performance has been measured for this circuit over the 18–26-GHz band.

B. rH-Kowari Topology

Fig. 5 shows the measured lower sideband up-conversion performance of a rH-Kowari mixer fabricated using the TRW 0.15-μm power HEMT process. The 1.8-GHz 0-dBm IF signal was split into I, $\overline{I}$, Q, and $\overline{Q}$ components with external passive circuitry before application to the four IF ports. Bias tees were used to superimpose −0.75 V dc onto these ac signals to bias the 120-μm-wide HEMTs just above their pinchoff voltage.

A key difference between the d-Kowari and rH-Kowari comes to the forefront when the circuits are pumped by the IF signal. In the d-Kowari case, the IF signal is passively combined with the LO before modulating the diodes. This prior combining does not happen in the rH-Kowari case. The IF pumps the HEMT gate and the LO is applied to the drain where its modulation effect is negligible for moderate LO signal levels. Hence, the fundamental operation of the rH-Kowari is to convert LO energy into RF under the control of the IF. Consequently, both the LO-to-RF and IF-to-RF conversion losses are dependent on the IF level and bias point and are relatively insensitive to the LO level, and the RF output level is largely determined by the LO and not the IF level. As shown in Fig. 5, the IF-to-RF conversion loss is about 2 dB over the 18–25.5-GHz RF band with a 0-dBm IF. This reflects the gate's efficiency in controlling the impedance seen by the LO signal as it looks into the HEMTs drain. The LO-to-RF conversion loss is approximately 13 dB over the band. The LO isolation, which measures the balance of the rat-race structure, is about 23 dB. Similar conversion loss and isolation results were measured when the circuit was configured for upper sideband operation.

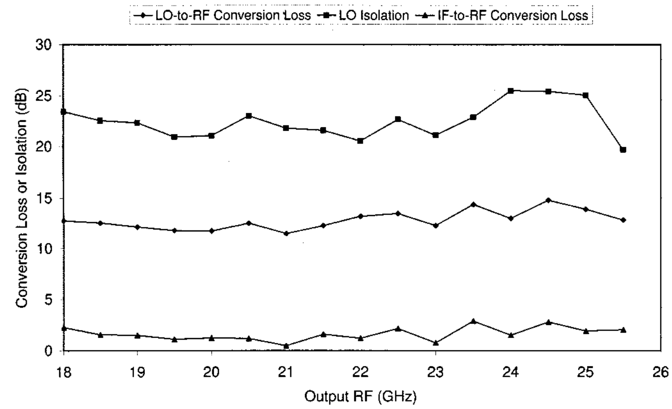


Fig. 5. Measured lower sideband LO-to-RF conversion loss, IF-to-RF up-conversion loss, and LO isolation of rH-Kowari over 18–25.5-GHz RF bandwidth.

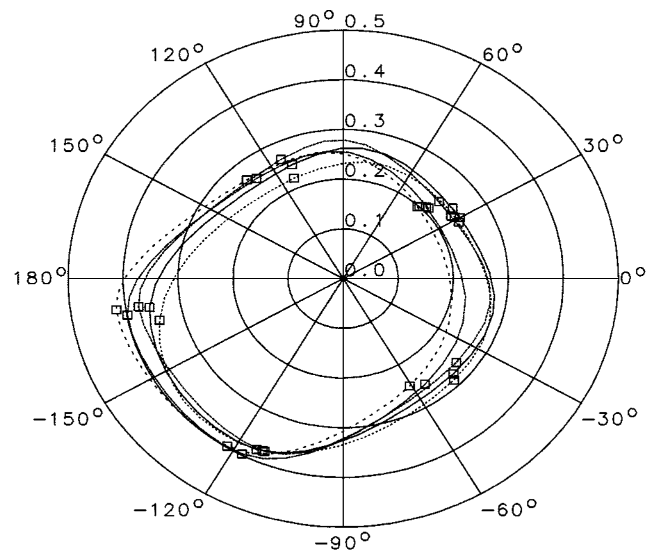


Fig. 6. Measured LO-to-RF transmission coefficient (i.e., S_{21}) loci of five rH-Kowaris at 25 GHz as θ is slowly varied using the auxiliary output from the HP8510 to drive a sine and cosine generator.

When the IF signals are replaced by quasi-dc control signals, the rH-Kowari mixer becomes a phase shifter. The operational difference between the rH-Kowari and the d-Kowari is the requirement for both the quadrature control signals and their inverses. Fig. 6 illustrates the measured phase-shift locus

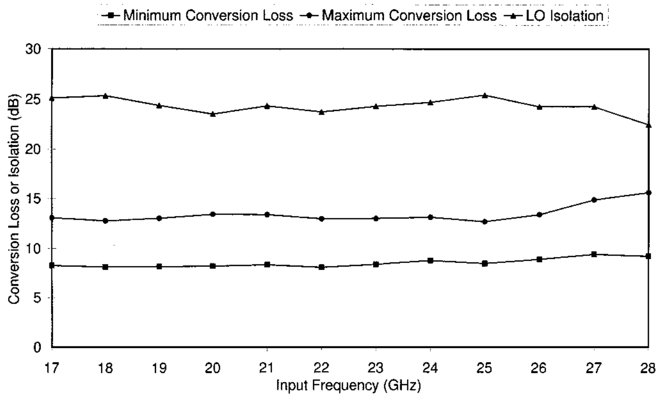


Fig. 7. rH-Kowari phase-shifter minimum LO-to-RF conversion loss, maximum LO-to-RF conversion loss, and LO isolation as a function of frequency from 17 to 28 GHz. These are equivalent to the maximum radius of the phase-shift circle (measured from the origin), minimum radius of the circle, and the circle center's offset from the origin, respectively.

of five circuits at 25 GHz as θ is slowly varied and shows an LO-to-RF insertion loss of between 8–14 dB. Fig. 7 shows the measured maximum and minimum LO-to-RF insertion loss, and the LO isolation for frequencies between 17–28 GHz. The LO-to-RF insertion loss and the LO isolation are similar to the values obtained from rH-Kowari up-conversion measurements. Together these measurements demonstrate both the wide-band nature of the phase-shifter performance and consistency between its operation as an up-converter and phase shifter.

IV. Conclusion

The combined use of a Lange coupler and resistive-HEMTs provides broader band and better performance than previously reported for rat-race mixers and phase shifters.

The mixer/phase-shifter design that has been described in this paper allows radios covering several commercial bands to use a common chipset, thus contributing to lower costs through more flexible manufacturing and inventory management.

The novel rH-Kowari has been demonstrated to provide more efficient up-conversion and more linear phase-shifting performance than the d-Kowari, although only the latter provides down-conversion functionality.

The rH-Kowari phase-shift loci are more circular than the d-Kowari loci due to the isolation of the active control element. The rH-Kowari's transmission attenuation is also much lower. The bandwidths of the d-Kowari and rH-Kowari circuits are similar due to the common nature of wide-band rat-race design at the core of both circuits.

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