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E-band transceiver monolithic microwave integrated circuit in a waveguide package for millimeter-wave radio channel emulation applications

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Dear editor,

In the development of 5G prototype systems and terminal demonstration platforms, a wireless channel emulator plays a crucial role in the test and verification process. With online and real-time simulation characteristics such as path loss, shadowing and multi-path fading of transmitted signals from antenna ports in a wireless environment, a wireless channel emulator can accurately measure the effects of wireless environments on system performance. This is a high-end universal instrument for verifying the performance of system devices and terminals in various complex scenarios. As 5G new radio applications develop rapidly, radio channel emulators that cover the millimeter-wave (mmWave) range are required, which have been rarely reported thus far. In the global market, Keysight first released its advanced PROPSIM channel emulator products along with multi-band transceivers, which support a frequency of up to 43.5 GHz [1]. However, in the 66–71 GHz band, which is one of the 5G mmWave spectrums approved at the World Radiocommunication Conference 2019 [2], similar high-performance emulators have not been reported publicly.

As massive multiple-input multiple-output (MIMO) technology and the corresponding theory have matured, the number of antennas in 5G systems has increased. Therefore, systematic conductive testing has become increasingly impractical because of long calibration times, confined spaces, high cost and exponentially increasing complexity in the mmWave band. By contrast, over-the-air (OTA) testing with multiple probes in a shielded anechoic chamber has become the main solution [3,4]. The channel emulator plays an essential role in a typical 5G mmWave massive MIMO OTA measurement setup. In the E-band (60–90 GHz), however, dozens of conventional coaxial connectors are required, which are bulky, costly, and very lossy. Therefore, a low-cost, compact, and low-loss solution is a key consideration in designing E-band transceivers for channel emulators. Moreover, the dynamic power range should be high enough to simulate various channel characteristics.

In this study, we present a mmWave transceiver monolithic microwave integrated circuit (MMIC) in a waveguide package. Highly selective band-pass and high-pass on-chip filters and multiple harmonic suppression techniques are employed to realize a compact transceiver module with a high dynamic output power range of up to 50 dB over a frequency range of 66–76 GHz. To the best of our knowledge, the proposed integrated module is the first demonstration of an E-band transceiver system for mmWave radio channel emulation applications.

Transceiver architecture. The transceiver MMIC is realized by cascading a few function blocks including a tripler, a first band-pass filter (BPF), an amplifier, a high-pass filter (HPF), a mixer and a second band-pass filter, as shown in Figure 1(a). A tripler, rather than a doubler or higher-order multiplier is chosen here to realize the trade-off between the local oscillator (LO) source cost and gain budget. The tripler, power amplifier (PA) and mixer are all nonlinear components, which means that various idle harmonic signals are generated. To obtain a high operational power range, all near- and in-band combination signal powers need to be kept sufficiently lower than the minimum useful signal power. Therefore, we choose an appropriate intermediate frequency (IF) to push the potential high-power harmonics out of the band of interest. Under normal conditions of LO, the fourth harmonic has a relatively higher power than the fifth one. For the 66–76 GHz band, the fourth harmonic of the LO frequency could be pushed out when the IF is chosen as 27 GHz. Out-of-band spurious signals could be effectively suppressed by low-cost and highly selective off-chip filters. Furthermore, new fourth and fifth harmonics could be converted from relatively higher-power, low-order harmonics because of mixer nonlinearity. An HPF is there-

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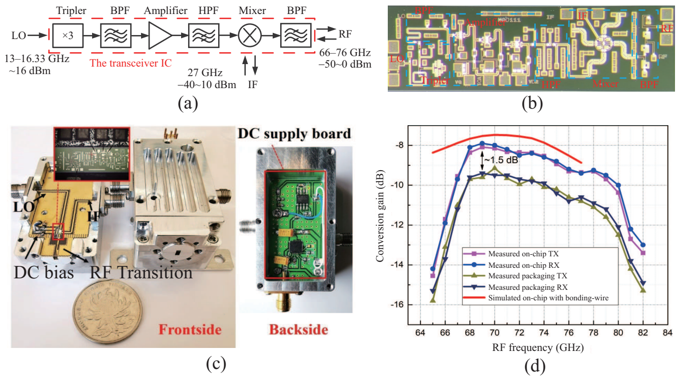

Figure 1 (Color online) (a) Block diagram of the transceiver MMIC (with frequency and power budget); (b) photograph of the MMIC (chip size: 2.7 mm× 0.9 mm); (c) photograph of the opened split-block and assembled module including MMIC and RF microstrip-to-waveguide transition; (d) simulated and measured conversion gain of the chip and module.

fore inserted before the mixer to further suppress the low-order harmonics. Considering low out-of-band suppression of the PA, another highly selective BPF is introduced before the PA. In addition, an on-chip compact BPF is utilized for additional out-of-band suppression.

MMIC and waveguide packaging design. The customized chip integrates a passive mixer with an LO chain and a BPF. The LO chain comprises a tripler followed by a PA, with two filters incorporated for harmonic suppression. As the mixer is passive, the chip can be used as both transmitter and receiver. The frequency tripler comprises an anti-parallel diode pair (APDP) and RF passive networks. Sufficient power is required for the APDP to generate odd-order harmonics while suppressing even order spurs. A compact seventh-order, highly selective BPF is applied after the tripler [5]. A 3-stage common source topology PA is adopted to obtain sufficient output power. Out-of-band rejection is an important part of our PA design. All harmonic signals from our LO chain could deteriorate the dynamic operating power range of the whole system. Therefore, a fifth-order HPF is employed after the amplifier. A modified star mixer with "S"-shaped Marchand balun stubs is used in the design to achieve a compact size. To reduce the coupling effect between these transmission lines, via fences are placed between the four "S"-shaped balun stubs and the IF port. For better spurious rejection, side Marchand balun coupling lines are grounded separately in the end, rather than joined together by the metal layer. The chip is fabricated using a commercial 0.1-μm GaAs pHEMT process with a die size of 2.7 mm × 0.9 mm including pads, as shown in Figure 1(b). To integrate the chip with a WR-12 waveguide package, a broadband microstrip-to-waveguide transition is printed on a TLY-5 thin film substrate. The photograph of the opened split-block and assembled module including the MMIC, and RF microstrip-to-waveguide transition is shown in Figure 1(c).

Measurement and results. The measurements are performed using two setups: on-chip characterization and waveguide packaging testing. Figure 1(d) illustrates the measured conversion gain of the MMIC chip and the integrated waveguide module with an IF frequency of 27 GHz. The on-chip measurement shows that the conversion gain is between −8 and −12 dB over the frequency range of 66–76 GHz. The measured conversion gain of the packaged waveguide module is approximately 1.2–1.5 dB smaller than that measured using on-chip testing. Apart from the microstrip-to-waveguide transition loss, the IF transmission line routed on the PCB also contributes to partial loss. For linear emulation transceiver applications, the dynamic power range of the system can be up to 50 dB considering a decent spurious rejection margin. When the transceiver operates at minimum input power, the signal-to-noise (SNR) ratio can be better than 8.8 dB over 66–76 GHz. In the other down-conversion measurement, the result is better than 54 dB with the same signal quality.

Conclusion. This study proposes and implements an E-band transceiver MMIC in a waveguide package. The waveguide module comprises a transceiver chip fabricated using a 0.1-μm standard GaAs pHEMT process and a microstrip-to-waveguide transition. Multiple filters and a high isolation mixer are appropriately designed to obtain better spur rejection. The IF frequency is carefully selected to avoid stronger in-band harmonics. Measurement results show that the waveguide module achieves a 50-dB power dynamic range at an appropriate SNR margin over a frequency range of 66–76 GHz. The total power consumption is 420 mW for one module. This implies that the specially designed E-band transceiver waveguide module can be effectively used in mmWave radio channel emulation applications.

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