RF Module for High-Resolution Infrastructure Radars

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We have developed a chipset consisting of a transmitter device, a receiver device, and a power amplifier by using our 3-D Wafer Level Chip Size Package technology that allows miniaturization and cost saving. Mounting the chipset to a printed circuit board, we have developed a radio frequency module for 76-GHz band infrastructure radars. The module is as small as 20 × 34.5 mm², in compliance with ARIB standard, and meets performance requirements for radar applications.

Keywords: 76-GHz band transceiver, WLCSP, RF devices, RF module

1. Introduction

Recently, various types of radar are being actively developed and commercialized with an eye toward eradicating traffic accidents. Attention is focused particularly on the use of millimeter-wave radar for collision prevention due to its excellent all-weather (rain, snow, and thick fog) performance and resolution. Now, in addition to the 76-77 GHz band, the 77-81 GHz band is being allocated for millimeter-wave radar application. To promote wider use of millimeter-wave products, it is essential to develop inexpensive devices.

We have developed radio frequency (RF) devices by using Wafer Level Chip Size Packaging (WLCSP) technology. WLCSP technology actualizes a miniature and reliable flip-chip assembly on a printed circuit board (PCB)*1 via tiny solder balls.[(1)-(4)] The developed RF devices were mounted to the PCB designed for the module. A compact transceiver (RF module) with a size of 20 mm × 34.5 mm was realized. The following chapters report on the chipset, PCB, and RF module we developed.

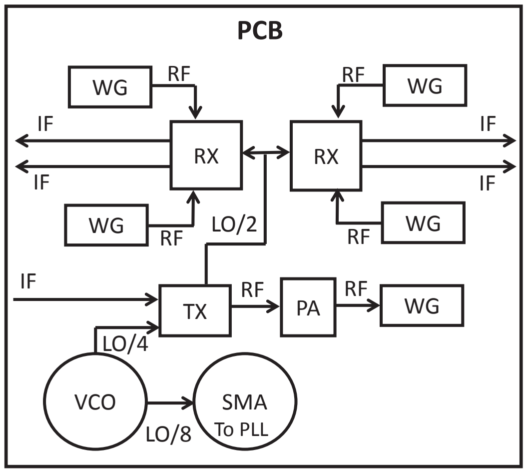

Fig. 1. Block diagram of the RF module

2. Development Target

The RF module to be developed composes millimeter-wave components other than the antenna. Figure 1 shows a block diagram of the RF module determined according to the design requirements for the radar system. The RF module has five waveguide (WG) ports (one for transmission and four for reception) with its PCB mounted with an oscillator (VCO), a transmission frequency converter (TX), reception frequency converters (RX), and a high output power amplifier (PA). With this setup, a signal from the transmission port is radiated forward and the reflected signal is received by the four antennas, thus allowing the direction of the reflected signal.

The major target specifications of the RF module determined according to the design requirements for the radar system are shown in Table 1. A sufficient margin must be maintained for the undesired signal power in order to comply with the standard of the Association of Radio Industries and Business (ARIB)*2.

The following chapters describe the RF devices, PCB, and RF module designed and produced as prototypes based on the RF module specifications.

Table 1. Target specifications of the RF module

Item	Min.	Typ.	Max.	Unit
Output power for TX	4.8	10	11.7	dBm
Gain for TX		10		dB
Spurious power for TX			-15	dBm
Gain for RX	5	8		dB
Noise Figure for RX		7	9	dB
Isolation from TX to RX	40	60		dB
Isolation form RX to RX	20	40		dB

3. Development of RF Devices

The WLCSP technology was applied to the main RF devices. The WLCSP structure is suitable for miniaturization with no need for packages. In addition, solder balls mounted in a grid pattern allow for mounting an RF device in the reflow process. The following are the prototype production results of main RF devices designed based on the target specifications of the RF module.

3-1 Frequency converter for the transmission

The signals radiated from the transmission frequency converter include not only the RF signal necessary for the radar but also local and image signals undesirably radiated. Figure 2 shows the relationship between the RF signal and main undesired radiation. The RF signal is generated as a frequency sum of the local and intermediate frequency (IF) signals and, at the same time, the image signal is generated as a frequency difference of the local and IF signals. In addition, the local signal leaks and is radiated as an undesired signal. According to the ARIB standard, the leakage power of undesired signal must be 0.5% or less (23 dBc or more) of the RF signal. In Table 1, the undesired signal power is set to -15 dBm or less (25 dBc or more) by taking the need for a margin into consideration.

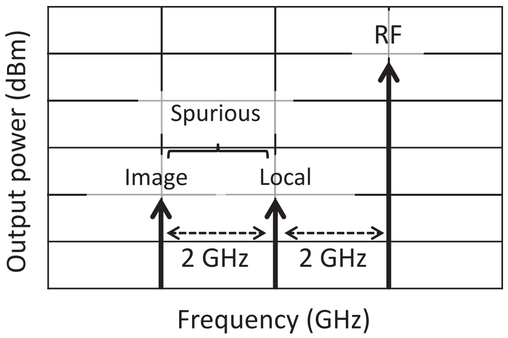

Fig. 2. Output signal of the frequency converter

Figure 3 shows a block diagram of the prototype transmission frequency converter produced. The transmission frequency converter comprises a 19-GHz band local amplifier, a frequency doubler, a 38-GHz band local amplifier, and double-balanced harmonic mixers. The frequency of the 19-GHz band local signal is doubled by the multiplier to drive the harmonic mixers. The IF signals (I+, I-, Q+, Q-) are converted into 76/79-GHz band RF signals by

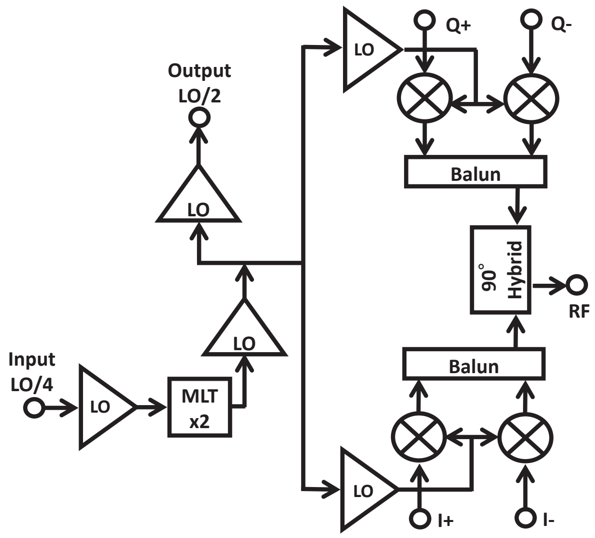

Fig. 3. Block diagram of the frequency converter

the harmonic mixers. The double-balance circuit changes the phase relationship between the local signals input to the four mixers of the same performance and the IF signals, and it also changes the phase relationship between the signals output from the individual mixers to combine the signals. By accurately designing these phase relationships, image and local (LO) signals are combined in a manner to cancel out each other and only RF signals are combined by being amplified four times and output. To achieve a target suppression of 25 dBc or more, it is necessary to achieve a phase accuracy of five degrees or less in the millimeter wave band. In the present study, the converter was designed with a line adjustment design error of 10 µm or less to achieve a phase difference of three degrees or less.

Figure 4 shows the prototype transmission frequency converter produced. The white circles arranged in a grid pattern in Fig. 4 are solder balls. The characteristics of the transmission frequency converter mounted to the PCB are shown in Fig. 5. The input power of the IF signal is 0 dBm and the input power of the local (LO) signal is 8 dBm. An RF signal is power of -14 dBm, the image and local signal powers are suppressed by 30 dBc or more and the characteristics obtained could adequately satisfy the ARIB standard.

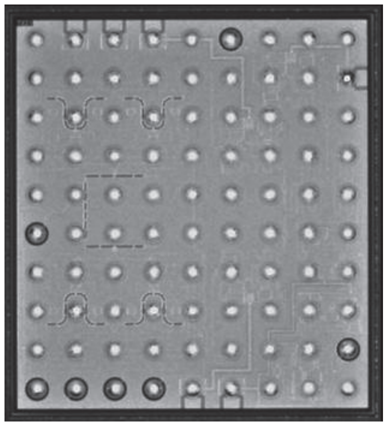

Fig. 4. The frequency converter (2.9 mm × 3.2 mm)

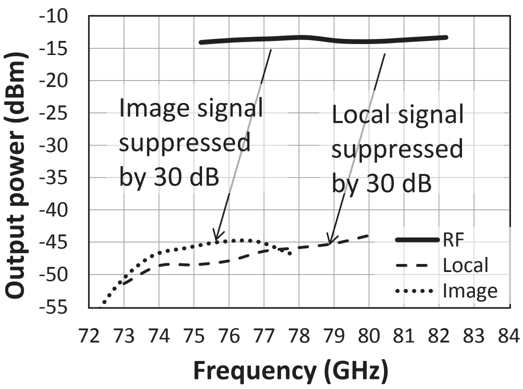

Fig. 5. Measurement result of the frequency converter

3-2 Frequency converter for the reception

For a reception frequency converter, a low noise figure (NF) is required to obtain a high sensitivity. In the case of a reception frequency converter, the NF is degraded because the noise in the image band is frequency-converted into the IF band. To prevent this NF degradation, a balance circuit for image signal suppression is adopted for the reception frequency converter as done for the transmission frequency converter to suppress the frequency conversion gain of the image signal. Figure 6 shows a block diagram of the reception frequency converter. For the reception frequency converter, a two-channel reception system is integrated into one device, which comprises a low noise amplifier (LNA), balanced harmonic mixers, and a local amplifier.

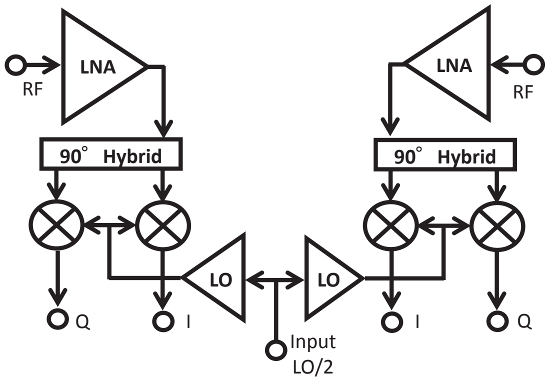

Fig. 6. Block diagram of the frequency converter

Figure 7 shows the designed reception frequency converter. The reception frequency converter is bilaterally symmetric and circuits for one channel are located on the right and left, respectively. The measurement results of the reception frequency converter mounted are shown in Fig. 8. Due to the effect of the balance circuit, the conversion gain of the image signal was suppressed by 30 dB and the NF of the reception frequency converter was equivalent to that of the LNA.

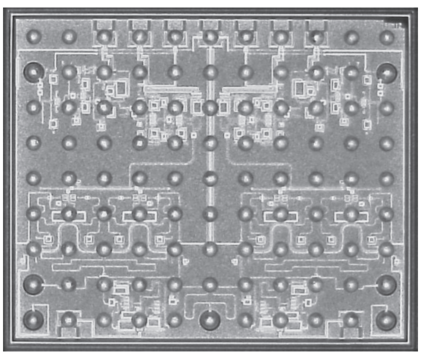

Fig. 7. Reception frequency converter (3.5 mm × 2.9 mm)

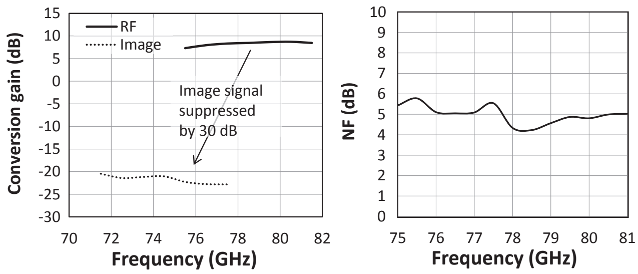

Fig. 8. measurement results of the frequency converter

3-3 Power amplifier

Figure 9 shows a block diagram of the power amplifier. The power amplifier consists of four stages of current-reuse amplifiers with a detector for power monitoring. A current-reuse amplifier has cascode connection,*[3] which can cut the current consumption by half, making it possible to miniaturize the DC line size. Figure 10 shows the prototype power amplifier produced. The power amplifier has the input port on the right side, the output port on the left side, and the DC and detector terminals on the lower side. The measurement results of the power amplifier mounted are shown in Fig. 11. In the radar frequency band (76-81 GHz), a gain of 25 dB or more and a saturated power of 20 dBm or more were obtained. Consequently, it was confirmed that the transmission frequency converter achieved an output power of 10 dBm in the back-off region with good linearity even including the loss at the PCB (about 1 dB).

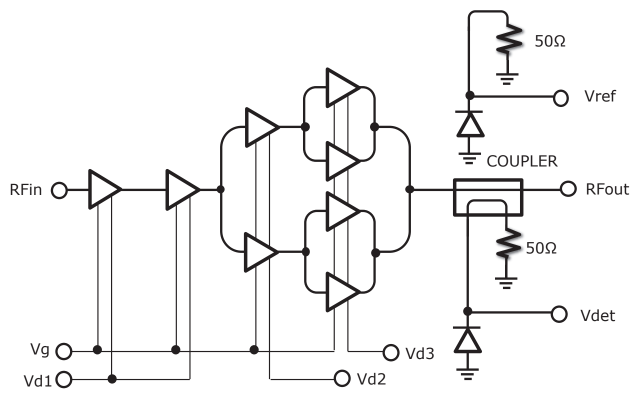

Fig. 9. Block diagram of the power amplifier

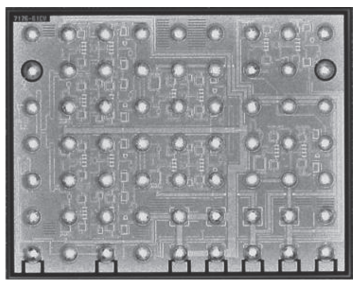

Fig. 10. The power amplifier (2.9 mm × 2.3 mm)

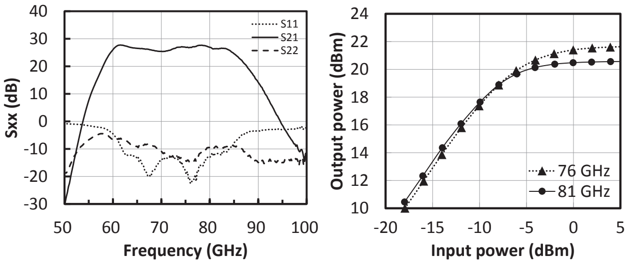

Fig. 11. Evaluation results of the power amplifier

4. Design of the PCB

For the RF module, wiring of many DC and signal lines is needed because multiple chips are mounted on the PCB. Since signals can be easily coupled between patterns in the millimeter wave band, lines must not be located adjacent to each other. In order to reduce the interference between lines as well as to reduce the PCB area, a four-metal-layer structure is used for the PCB as shown in Fig. 12. The top layer, where the loss in the millimeter wave band is minimum, is used for the signal line. The DC line is provided across the ground (GND) plane from the signal line to reduce the interference with the signal line.

For the waveguide port, the micro strip line (MSL) with a back-short is adopted for a low conversion loss across a broad band. The structure of the waveguide transition section is shown in Fig. 13. This section must be designed to minimize loss because its loss directly affects the transmission power and the NF characteristics. For this structure, the loss can be reduced by forming a waveguide structure in a direction vertical to the board and providing an antenna of λ/4 and a back-short section λ/4 above the antenna. The measurement results of the waveguide transition section are shown in Fig. 14. For S11, good characteristics of -18 dB or less were obtained with respect to a target of -15 dB or less with no influence on the PA and antenna. As for S21, low-loss characteristics of about 0.5 dB were obtained.

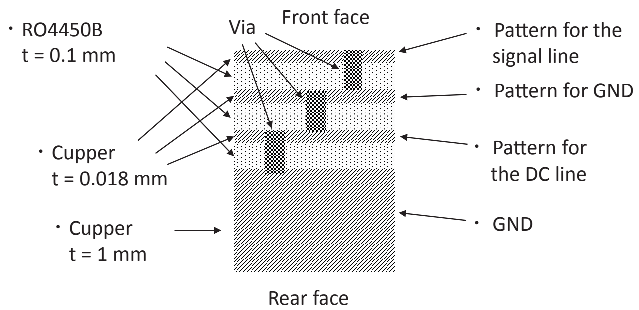

Fig. 12. PCB layer structure

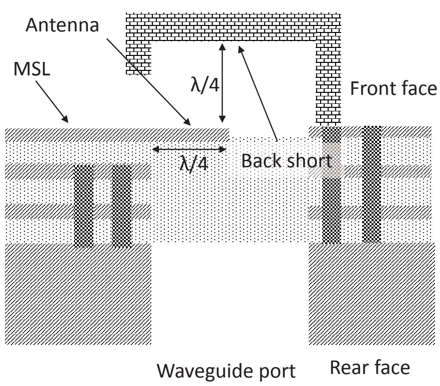

Fig. 13. Cross section of the waveguide port

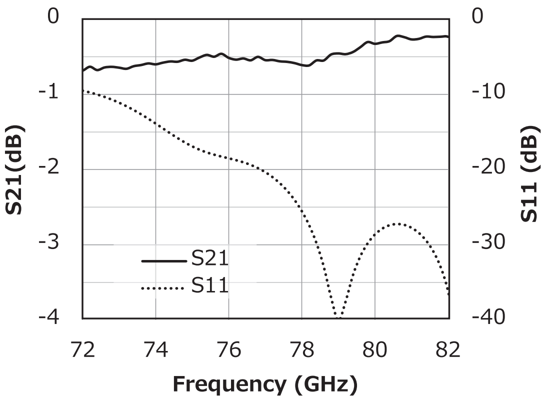

Fig. 14. Measurement results of the MSL-WG section

5. Trial Results of RF Module

Figure 15 shows the prototype RF module produced. The module has the structure shown in Fig. 1 with the RF devices, back-short, VCO, and other components mounted on the PCB. A VCO with InGaP HBT was used.[(5)] Waveguide ports (one for the TX and four for the RX) were arranged on the rear face. The RF module was miniaturized to a size of 20 mm × 34.5 mm by using WLCSP.

The transmission characteristics of the RF module are

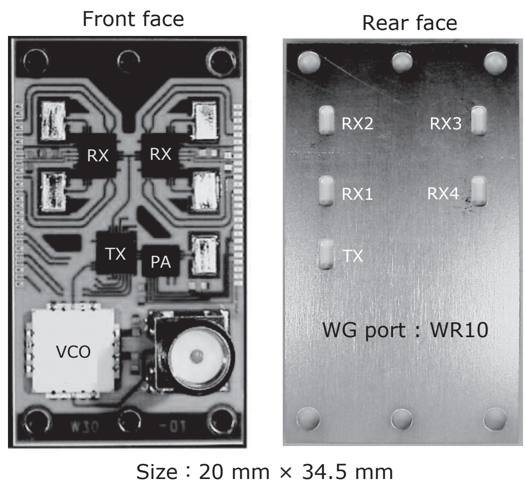

Fig. 15. Prototype RF module produced

shown in Fig. 16. The module achieved a specified output power of 10 dBm. The output power of the image and local signals was about -20 dBm, adequately satisfying the ARIB standard for undesired signals. Figure 17 shows the reception characteristics. The conversion gain was 9 dB and the NF was 6 dB, both achieving the target values. Figure 18 shows the isolation characteristics. The isolation between transmission and reception shows the attenuation of the transmission signal received not via the waveguide port. If this value is low, the radar cannot detect the reflected signal. In the present study, the isolation between transmission and reception was 40 dB or more and characteristics exceeding the target were obtained. The isolation between reception ports shows the attenuation of the signal input to a different RX port. If this value is low, the angular resolution of the radar decreases. In this study, the isolation between reception ports was 30 dB or more, resulting in good values.

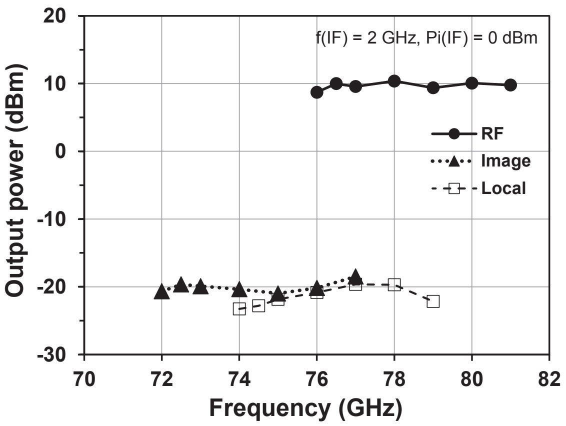

Fig. 16. Output power of the RF module

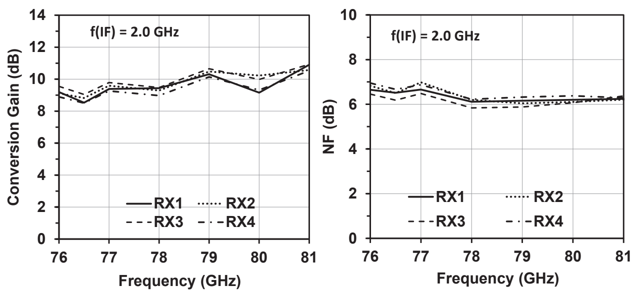

Fig. 17. Reception characteristics of the RF module

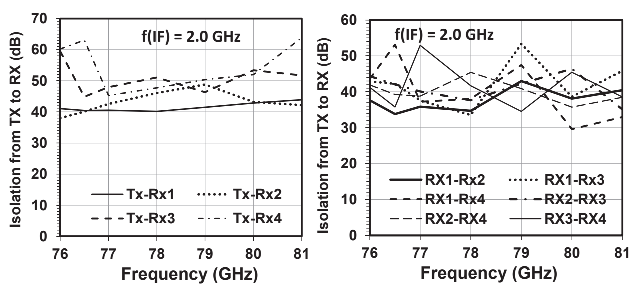

Fig. 18. Isolation characteristics of the RF module

Table 2 shows the list of the RF module evaluation results. As shown in the table, the prototype RF module satisfied the target specifications.

Table 2. Measurement results for the RF module

Item	Specification			Trial results			Unit
	Min.	Typ.	Max.	Min.	Typ.	Max.	
Output power for TX	4.8	10	11.7	8.7	10	10.3	dBm
Gain for TX		10			10		dB
Spurious power for TX			-15			-19	dBm
Gain for RX	5			9			dB
Noise Figure for RX			9			7	dB
Isolation from TX to RX	40			40			dB
Isolation form RX to RX	20			30			dB

6. Conclusion

RF devices for infrastructure radars were developed using our original WLCSP technology. The RF devices were mounted to the PCB designed to produce a prototype RF module. The prototype module complied with the ARIB standard and satisfied all the specifications required for radar. The WLCSP technology that eliminates the need for packages also contributed to the miniaturization of the RF module to a size of 20 × 34.5 mm^2.

7. Acknowledgements

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Technical Terms

*1 Printed circuit board (PCB): A fine metallic wiring pattern made of, for example, copper formed on a dielectric material board. A PCB is mounted with components such as resistors, capacitors, and IC chips. Also called a printed wiring board (PWB) before components are mounted, because no circuit has yet been formed.

*2 ARIB standard: A Japanese standard for radio wave use, which is established by the Association of Radio Industries and Businesses

*3 Cascode connection: A method for connecting two field effect transistors (FETs), whereby the source of one transistor is connected to the drain of the other transistor with the remaining source earthed to GND and the remaining drain DC biased. While the voltage is doubled, the current can be halved.

References

(1) K. Tsukashima, M. Kubota, A. Yonamine, T. Tokumitsu, and Y. Hasegawa, "E-band radio link communication chipset in cost effective wafer level chip size package (WLCSP) technology," in Proc. of the 6th European Microwave Integrated Circuits Conference, Manchester, pp. 29-32 (Oct. 2011)

(2) T. Kawasaki, M. Kubota, K. Tsukashima, T. Tokumitsu, and Y. Hasegawa, "A full E-band low noise amplifier realized by using novel wafer-level chip size package technology suitable for reliable flip-chip reflow-soldering," in IEEE International Microwave Symposium Dig., Tampa Bay, TU3G-1 (June 2014)

(3) K. Tsukashima, O. Anegawa, T. Kawasaki, A. Otsuka, M. Kubota, T. Tokumitsu, S. Ogita, "Transceiver MMIC's for street surveillance radar," 2016 11th European Microwave Integrated Circuits Conference (EuMIC), pp. 329-332 (Oct. 2016)

(4) O. Anegawa, T. Kawasaki, K. Tsukashima, M. Kubota, T. Tokumitsu, S. Ogita, "A WLCSP 79-GHz band harmonic mixer with high LO-leakage suppression," 2016 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT), pp. 1 – 3 (Aug. 2016)

(5) T. Kawasaki, A. Otsuka, M. Kubota, T. Tokumitsu, S. Ogita, "Improvement of 19 GHz VCO with use of Feedback Coupled-Line Resonator," 2015 European Microwave Conference (EuMC), pp. 239 – 242 (Oct. 2015)

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