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G-Band Sub-Harmonic Mixer with Broadband and Low Conversion Loss

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Abstract—In this paper, two G-band sub-harmonic mixers based on planar antiparallel Schottky diodes are presented. The proposed type-I mixer is designed using the conversional THz Schottky diode mixer circuit architecture. In order to broaden the bandwidth further, a novel type-II sub-harmonic mixer based on new circuit topology is proposed. In type-II mixer, an antiparallel Schottky diodes chip is directly connected with metal ground using silver epoxy. The simulated results show that the single-sideband (SSB) conversion loss of type-II mixer is less than 10 dB in the frequency range of 158.2–194.6 GHz. For validation, the type-I mixer is fabricated and tested. Measurement results show that the single-sideband conversion loss of type-I mixer is basically less than 10.7 dB in the frequency range of 166–190 GHz.

1. INTRODUCTION

With the increasing demand of high-resolution detection and high sensitivity for planetary and atmospheric science, space-borne instruments are moving towards terahertz (THz) frequency range, which is often described as the final unexplored area of spectrum [1]. Compared with millimeter wave heterodyne receivers, THz heterodyne architecture receivers can provide unrivaled spectral resolution and sensitivity for observations and detections. Due to the lack of commercially available low-noise amplifiers in THz band, planar Schottky diode mixer is widely used in the first stage of the heterodyne receiver front-ends to down-convert the collected THz signals to microwave frequencies that are easier to process. Being the first stage of the receiver front-ends, Schottky diode mixer plays a crucial role in the overall performance of the receiver. Recently, various high performance sub-harmonic mixers have been documented [2–11]. In [3], a 199–238 GHz sub-harmonic mixer using a two-stage reduced matching technology and Global Design Method is proposed. In this design, a broad bandwidth is successfully achieved; however, the higher conversion loss should be further reduced. In [4], a sub-harmonic mixer, whose single-sideband (SSB) conversion loss is less than 9 dB in the range of 208–229 GHz, is presented. By accurate diode modeling, low conversion loss is obtained. In [6], a 183 GHz sub-harmonic mixer, where a grounding low-pass filter (LPF) is added near the DC ground, is presented. In this design, the grounding LPF is used to suppress the coupling of the RF signal to the ground. The measured results show that SSB conversion loss is less than 10.6 dB in the RF bandwidth of 173–191 GHz. Although the mixer exhibits the excellent performance, the relatively narrow bandwidth still restricts its application in THz communication systems.

In this paper, two G-band sub-harmonic mixers based on planar antiparallel Schottky diodes are presented. The proposed type-I mixer is designed using the conversional THz Schottky diode mixer circuit architecture. In order to broaden the bandwidth further, a novel type-II sub-harmonic mixer based on new circuit topology is proposed. In type-II mixer, an antiparallel Schottky diodes chip is directly connected with metal ground using silver epoxy. The proposed new mixer can minimize the circuit size, broaden the bandwidth, and reduce the conversion loss. The simulated results show that

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the single-sideband (SSB) conversion loss of type-II mixer is less than 10 dB in the frequency range of 158.2–194.6 GHz. For experimental validation, the type-I mixer is fabricated and tested. Measurement results show that the single-sideband conversion loss of type-I mixer is basically less than 10.7 dB in the frequency range of 166–190 GHz.

2. W-BAND LO SIGNAL GENERATOR

The schematic of W-band LO generator is sketched in Fig. 1, which includes a multiplier, a W-band power amplifier, and a microstrip-to-waveguide probe. The multiplier is designed for W-band applications, and the circuit is manufactured with a 0.1 µm gate length GaN HEMT process. The recommended input power of the multiplier MMIC is 13 dBm @10 $\sim$ 11.75 GHz, while the output power can reach 14 dBm @80 $\sim$ 94 GHz. The MMIC power amplifier is also manufactured with GaN HEMT process and includes three amplifier stages designed for applications in the 88 to 96 GHz frequency range. The amplifier can provide 13 dB of gain, 25 dBm of saturated power from a +15 V supply voltage. The configuration of the microstrip-to-waveguide probe is shown in Fig. 2(a), in which the microstrip probe circuit is printed on a substrate of Rogers RT/duroid 5880 with a thickness of 0.127 mm, relative dielectric constant of $\varepsilon_r = 2.2$, and loss tangent of $\tan\delta = 0.0009$. The simulated results are plotted in Fig. 2(b), which indicates that the return loss is better than 20 dB in the frequency range of 71–107 GHz.

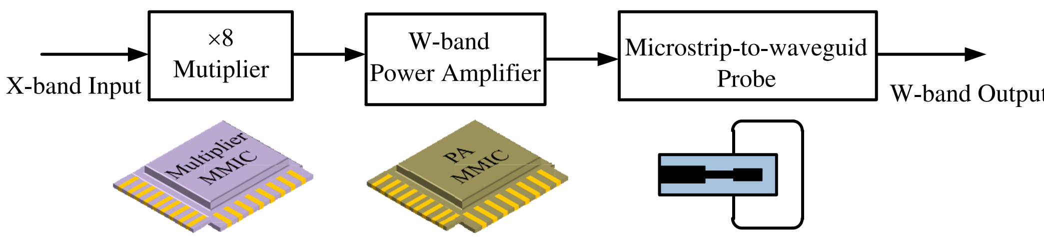


Figure 1. The schematic of W-band LO generator.

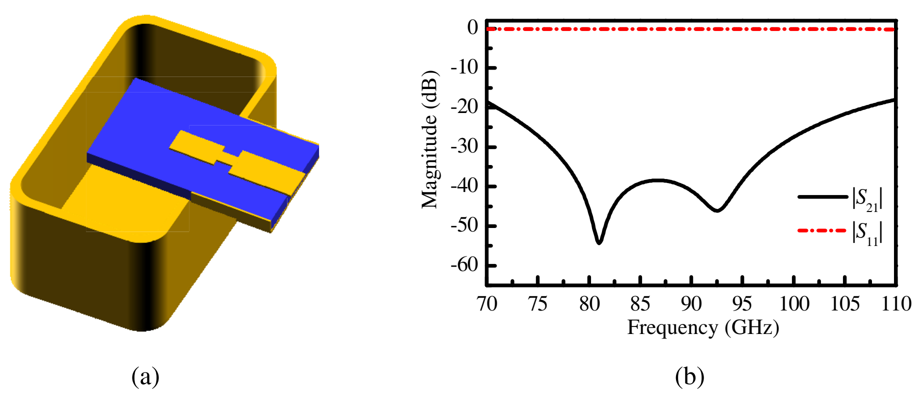


Figure 2. (a) Configuration of W-band microstrip-to-waveguide probe, (b) simulation results.

3. SUB-HARMONIC MIXER DESIGN

3.1. Schottky Diode Model

As the operating frequency moves towards THz band, the parasitic capacitance and inductance caused by diode packaging and physical size become more significantly. In Fig. 3, a 3-D electromagnetic model of planar antiparallel Schottky diodes is presented [5, 12–15]. Based on this accurate model, the parasitic effects will be fully considered. For Schottky diode, it is usually characterized by DC parameters of

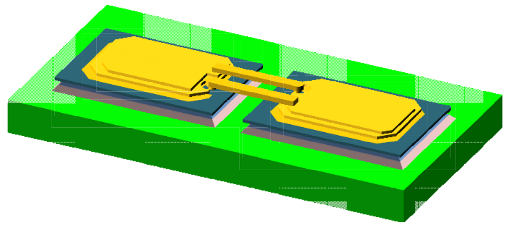


Figure 3. The 3-D electromagnetic model of planar antiparallel Schottky diodes.

C_{j0}, R_s, I_s, n, and V_j, where C_{j0}, R_s, I_s, n, and V_j denote the zero-bias junction capacitance, series resistance, saturation current, ideal factor, and junction potential, respectively.

$$f_c = \frac{1}{2\pi C_{j0} R_s} \tag{1}$$

In this design, a commercial high performance Schottky diode with $C_{j0} = 4\,\mathrm{fF}$, $R_s = 5\,\mathrm{Ohm}$ is chosen. According to Eq. (1), the cut-off frequency of the chosen diode is about 7.96 THz, which can fully satisfy the design requirements.

3.2. Type-I G-Band Mixer

As shown in Fig. 4, the conventional circuit topology of the type-I mixer is given. In Fig. 4, an antiparallel Schottky diodes chip is placed between the RF probe and LO lowpass filter. Standard WR-5 and WR-10 waveguides are employed for RF port and LO port, respectively. The corresponding passive circuit is shown in Fig. 5, which consists of RF and LO E-plane probes, a LO lowpass filter, an IF lowpass filter, RF/DC grounding, and Schottky diodes.

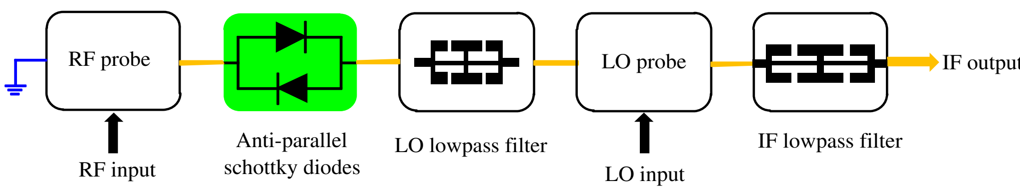


Figure 4. Circuit topology of type-I mixer.

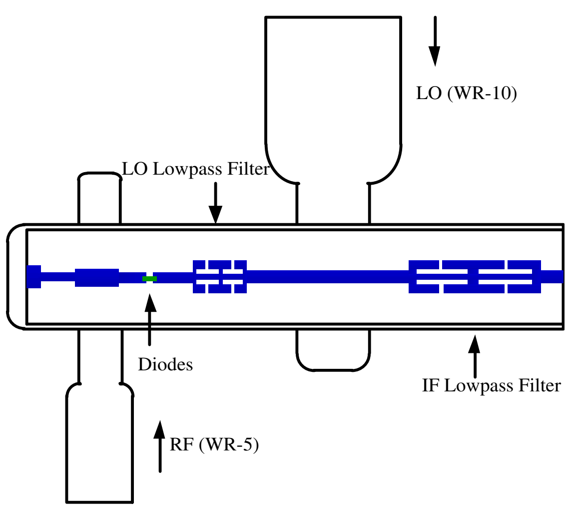


Figure 5. Configuration of type-I mixer.

In order to obtain a better suppression in out-of-band, traditional high-low impedance lowpass filters are usually designed with high order, which result in larger circuit area and higher insertion loss. Because compact microstrip resonant cell (CMRC) is of high rejection level and compact size, CMRC structure is wildly adopted to design a high performance lowpass filter. As shown in Figs. 6(a) and 6(b), the frequency responses of IF lowpass and LO lowpass filters based on a CMRC structure are presented, respectively. It can be found that the designed IF lowpass filter can provide high rejection level to suppress LO signals, and the designed LO lowpass filter can provide more than 40 dB suppression to choke RF signals.

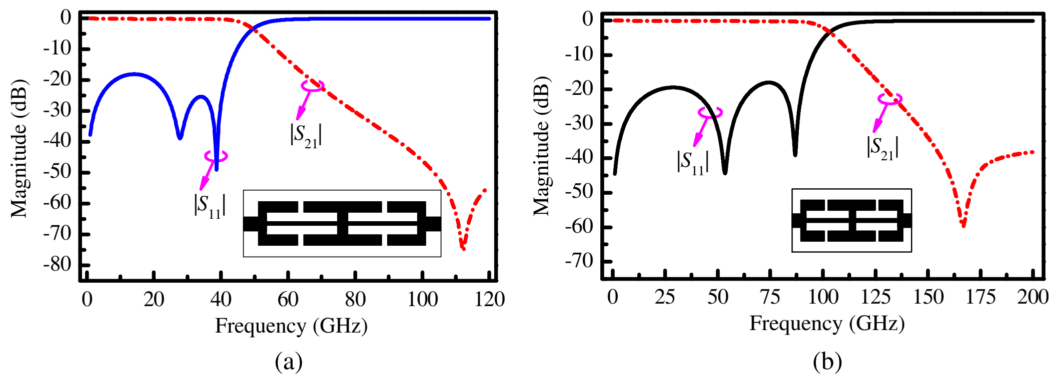


Figure 6. Frequency responses of (a) IF lowpass filter, (b) LO lowpass filter.

3.3. Type-II G-Band Mixer

As can be seen, in conversional THz Schottky diode mixer circuit architecture, RF probe is connected with the DC ground using a quarter-wave length transmission line usually to realize RF virtual grounded [2–13]. Therefore, the RF signal has the limitations on bandwidth according to transmission line theory. Besides, RF grounded circuit is one part of the matching circuits, which increases the complexity and difficulty of the design process.

To solve the problem mentioned above, a new kind of circuit architecture of mixer is proposed in Fig. 7, where an antiparallel Schottky diodes chip is directly connected with metal ground using silver epoxy. Based on this architecture, RF probe matching circuits can be considered individually. Therefore, the complexity and difficulty of the design process can be reduced. Longitudinal view of the proposed mixer is shown in Fig. 8, which consists of RF and LO E-plane probes, LO lowpass filter, IF lowpass filter, RF/DC grounding, and Schottky diodes.

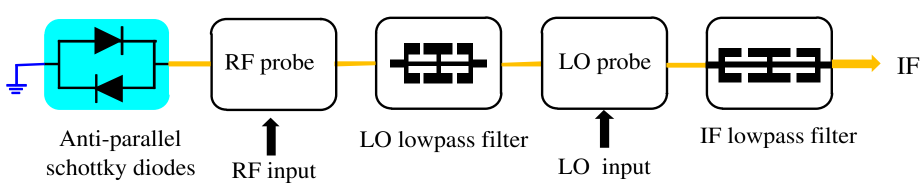


Figure 7. The new circuit topology of type-II mixer.

The simulated SSB conversion loss of proposed type-II mixer is plotted in Fig. 9. As can be seen, the conversion loss is less than 10 dB in the frequency range of 158.2–194.6 GHz. The fraction bandwidth of proposed mixer can reach 20.6%. Besides, the circuit size of the quartz glass is very compact, which occupies only 4.865 mm $\times$ 0.45 mm.

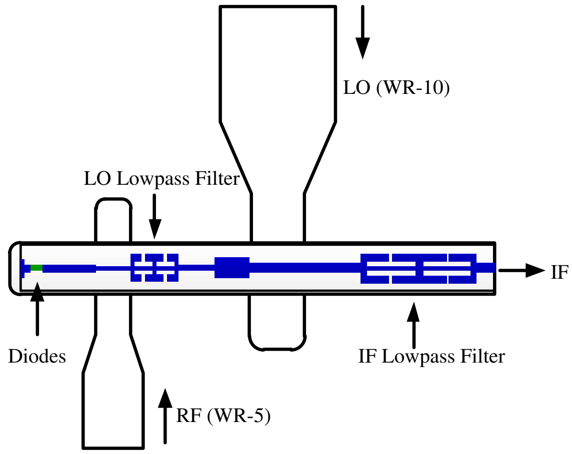


Figure 8. Longitudinal view of type-II mixer.

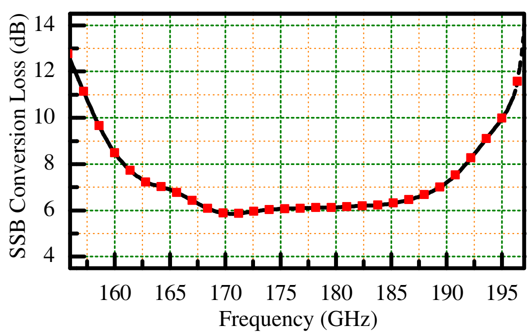


Figure 9. The simulated SSB conversion loss of type-II mixer.

4. FABRICATION AND MEASUREMENT OF TYPE-I MIXER

The split-cavity of G-band type-I mixer is fabricated with brass using high precision computer numerical control milling, and its surfaces are coated with 1 μm gold. Fig. 10(a) shows a photograph of the type-I mixer, whose physical dimension is 20 mm × 21.11 mm × 20 mm, which is very compact. The internal circuit of the mixer is presented by microscope, which is shown in Fig. 10(b). As can be seen, the diode chip is flipped on the substrate of 50-μm quartz using silver epoxy. In type-I mixer, RF grounded is realized by a quarter-wave length microstrip transmission line.

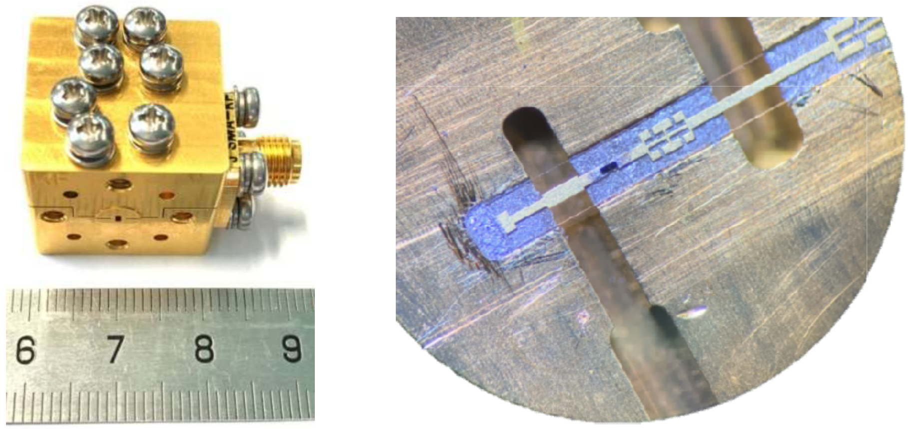
The measurement system of G-band sub-harmonic mixer for calculating SSB conversion loss is depicted in Fig. 11. All relevant instruments and modules must be calibrated before testing. In this work, the insertion loss of the coaxial line is tested by Agilent N5244A vector network analyzer (VNA). The output power of ×12 multiplier is measured by AV2436A power meter, and the insertion loss of G-band variable attenuator is calibrated by Keysight PNA-X N5247A with frequency extender. In this design, the input LO signal is fixed at 90/91.5 GHz, and its power is calibrated by W-band power meter. The measurement of the G-band sub-harmonic mixer is carried out at room temperature.

In Fig. 11, the operating frequency of IF output signal and SSB conversion loss can be expressed as:

$$f_{IF} = |f_{RF} - 2f_{LO}| \tag{2}$$

$$CL = |P_{IF}(\text{dBm}) - P_{RF}(\text{dBm}) - IL(\text{dB})| \tag{3}$$

where f_{IF}, f_{RF}, and f_{LO} denote the IF frequency, RF frequency, and LO frequency, respectively. In Eq. (3), CL, P_{IF}, P_{RF}, and IL represent the conversion loss, IF power, RF power, and insertion loss of the coaxial line, respectively.



(a) (b)

Figure 10. (a) Photograph of type-I mixer, (b) Photograph of the circuit after mounting into the half of the split metal block.

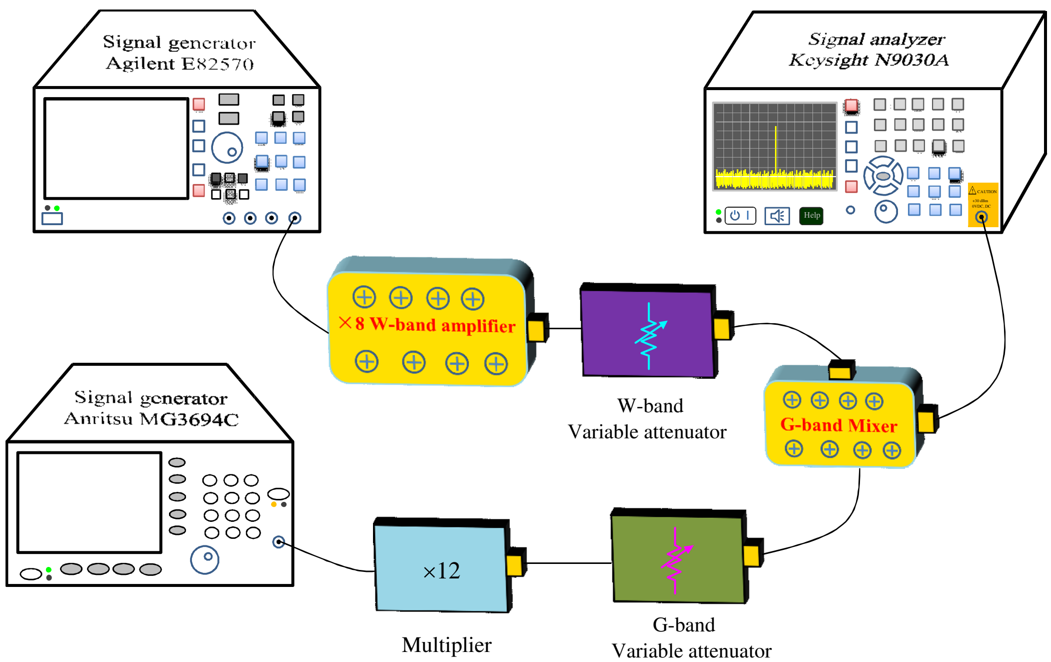


Figure 11. The measurement system of type-I mixer.

In this work, f_{LO} is chosen at 90/91.5 GHz with fixed output power of 8 mW, and the RF input power is about −20 dBm. The measurement SSB conversion loss is plotted in Fig. 12(a), when f_{LO} is fixed at 90 GHz. As can be seen, the measured SSB conversion loss of G-band mixer is basically less than 10.7 dB in the frequency range of 166–190 GHz. The minimum SSB conversion loss can reach 7.77 dB @ 180 GHz. When f_{LO} is fixed at 91.5 GHz, the SSB conversion loss is basically less than 10.67 dB in the frequency range of 166–190 GHz, as shown in Fig. 12(b). The measurement results are in good agreement with the simulation ones. It can be found that the measured SSB conversion loss has a slight offset in spectrum compared with the simulation ones, which is mainly attributed to the Schottky diode parasitic effects, fabrication errors, and manual assembly errors.

The comparison between this work and other reported sub-harmonic mixers is summarized in Table 1, which shows that the proposed G-band sub-harmonic mixer has wide frequency band, low conversion loss, and compact circuit size.

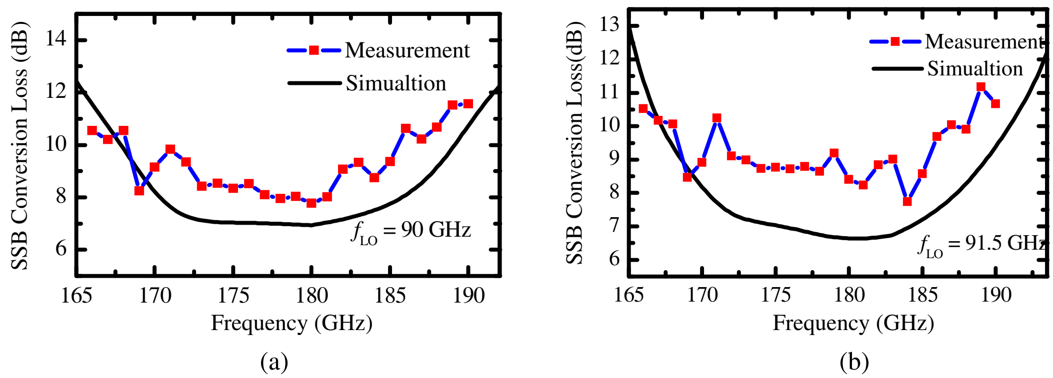


Figure 12. The measurement and simulation SSB conversion loss of type-I mixer, (a) $f_{LO} = 90\,\text{GHz}$, (b) $f_{LO} = 91.5\,\text{GHz}$.

Table 1. Comparison between this work and some reported works.

Ref.	Frequency (GHz)	FBW (%)	SSB Conversion Loss (dB)	Circuit Length (mm)
[2]	290–310	6.67	< 10	-
[3]	199–238	17.8	< 12.7	5.232
[4]	208–229	9.6	< 9	10.81
[5]	211–226	6.86	< 12	8.908
[6]	173–191	9.89	< 10.6	-
This work	166–190	13.5	< 10.7	5.11

5. CONCLUSION

In this paper, two planar Schottky diode G-band sub-harmonic mixers are presented. The type-I mixer is designed using a conversional circuit architecture, and measurement results are in good agreement with the simulation ones. For better performance, a new circuit topology is employed in G-band mixer design. The simulation results of type-II mixer show that SSB conversion loss is less than 10 dB in the frequency range of 158.2–194.6 GHz. The proposed two G-band mixers are of broadband bandwidth, low conversion loss, compact circuit size, and low cost, which make the mixer attractive in THz communication systems.

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