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Transmitarray Element Design for Subharmonic Injection-locked RTD Oscillators in THz Band

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Abstract— In this paper, a transmitarray element (TE) is designed for wireless subharmonic injection-locked triple barrier (TB) resonant tunneling diode (RTD) oscillators. It adopts a receiver antenna (RA)-transmitter antenna (TA) structure. The RA is a u-slotted patch antenna, and we use a cubic silicon block at top of this patch, so as to increases the RA gain and radiation efficiency. A fat monopole structure with a slot-like counterpoise is used as the TA. In this design, the RA can receive 100 GHz subharmonic injection signal (SIS). Meanwhile, the TA will radiate the 300 GHz fundamental oscillation signal (FOS) generated by the TB RTD. Moreover, the TA structure can isolate the 300 GHz FOS coming into the RA but couple the received 100 GHz SIS to the TB RTD, which performs like a filter-antenna. In the simulation, the transmission loss in the TA structure is higher than 15 dB around 300 GHz and only about 1.5 dB around 100 GHz. The gain of RA is 6 dBi with 65% radiation efficiency at 100 GHz and the gain of TA is 14 dBi at 300 GHz when applying a 1 mm radius silicon lens at the backside of the InP substrate.

1. INTRODUCTION

THz research has drawn much attention in recent years, as the large frequency bandwidth availability and short wavelength mean THz technology has great potential in high data volume communication and high-resolution radar applications [1, 2]. As one of the most important parts in a THz system, a high-quality source is critical. RTD is a kind of negative differential resistance source that can operate at very high frequencies [3], making it an attractive choice as a THz source. TB RTD is fabricated by adding an additional barrier to the traditional double barrier, allowing it to perform as a detector at zero voltage bias [4]. However, in RTD oscillators, because of parasitic parameters and fabrication uncertainty, there usually exists a high level of phase noise and a wider spectrum in high frequencies. Besides this, it is difficult to design the phase control element at the THz band, e.g., a phase-locked loop. Therefore, we propose to utilize the lower frequency SIS to control the phase and oscillation of the TB RTD oscillator. For a subharmonic injection locking process, the received SIS will be multiplied by TB RTD due to its nonlinearity. While the multiplied SIS frequency is close to the FOS frequency, the injection locking phenomenon will happen [5]. Another merit in the injection locking system design is that the phase noise characteristic of the TB RTD oscillator will follow the injection signal [6]. Therefore, we can decrease the phase noise of the TB RTD oscillator by applying a low phase noise SIS.

In [7–9], the authors designed wireless subharmonic injection models for oscillators, which proved quiet flexible in realistic application. In these wireless injection systems, we can chose almost any commercial injection source without changing it. However, the SIS source is in the oscillator radiation side in [7–9]. There are mainly two drawbacks to this design. As shown in Fig. 1(a), firstly, the SIS antenna and the oscillator antenna will suffer from angle misalignment loss. Secondly, if the SIS source is exactly above the oscillator, the radiation pattern of the oscillator antenna will be shadowed by the SIS source. This phenomenon will become serious when the SIS source is close to the transmitter. A trade off design has to be considered between the injection path distance and the oscillator antenna radiation performance. In any case, it is impossible to achieve an efficient and compact wireless injection locking system in Fig. 1(a) wireless injection structure. What we expect the system is like in Fig. 1(b), whereby the SIS source is at the opposite side of the oscillator radiation. In that situation, the antenna can receive the SIS at the backside, and meantime, radiate the FOS at the front side. As such, a TE is proposed in this paper. Compared with conventional designs, our TE works at two frequency bands. Further, the TE in this paper also achieves high isolation at the fundamental oscillation frequency and a high coupling pass at the subharmonic injection frequency. Section 2 presents the TE design and simulation results

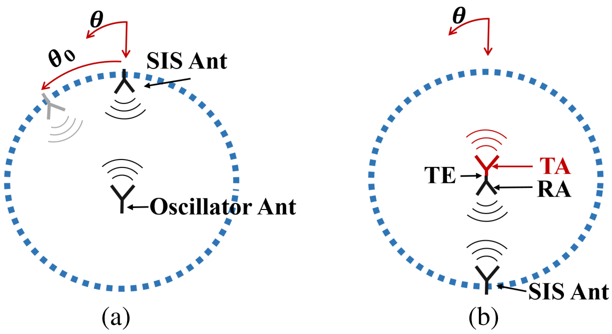

Figure 1. Schematic of wireless subharmonic injection system. (a) conventional setting with the SIS source on the side of oscillator antenna radiation; (b) SIS source on the opposite side of the radiating oscillator antenna.

2. ANTENNA DESIGN AND SIMULATION RESULTS

2.1. Transmitarray Element Design

In the design of this paper, the SIS frequency is 100 GHz and the FOS frequency of the TB RTD is 300 GHz. Which corresponds to the RA working at 100 GHz where the TA is operating at 300 GHz. The TE is designed on the InP substrate, where processing the TB RTD oscillator. The TE configuration is shown in Fig. 2. The bottom layer consists of a 350 µm thick InP substrate followed by a slotted ground layer made of gold (as all metal layers) with a thickness of 0.5 µm. Then a 2.5 µm benzocyclobutene (BCB) dielectric spacer layer is deposited on top of the ground layer for the electrical isolation between the fat monopole and the slotted ground. The fat monopole is then deposited on the BCB layer, resulting in a similar structure as in [10]. After that, the monopole layer is covered by another 17.5 µm thick BCB film. Lastly, the receiver antenna — a u-slotted receiver patch antenna that is connected to the monopole — mounted on top of the thick BCB layer. In this receiver antenna structure, a higher radiation efficiency can be expected especially for thick BCB layers. For example, in the 100 GHz band, 80% radiation efficiency can be achieved while employing an around 80 µm BCB substrate in conjunction with a conventional patch antenna design. However, such a thick BCB layer is difficult to deposit and decreases the 100 GHz signal coupling efficiency in the TA part. Here we choose a 17.5 µm BCB layer in the design. In order to increase both the radiation efficiency and the gain of the patch antenna in such thin substrate condition, we added a cubic silicon block on the surface of the patch.

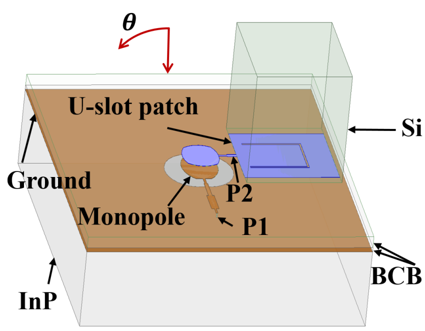

Figure 2. Configuration of the proposed transmitarray element (TE).

There are mainly three aspects to evaluate within our TE design. The first aspect is whether the RA receives the SIS efficiently. We can assess this through observing the TE gain at $\theta = 0°$ in the 100 GHz band, which should be high, meaning that the RA can receive a strong SIS. The second aspect addresses the question whether the TA radiates efficiently to the FOS. In a similar way, we can assess this through observing the TE gain at $\theta = 180°$ degrees around 300 GHz, where the gain should be high, indicating that the TA efficiently radiates towards the FOS. The third aspect focuses on whether the TA part isolates the FOS from the RA while coupling the SIS into the TB RTD oscillator. Which means that the transmission loss between port P1 and P2 should be low in the 100 GHz band and large at 300 GHz.

2.2. Simulation Results and Analysis

All simulations in this paper are carried with the full-wave computational electromagnetic platform ANSOFT HFSS. The permittivity of BCB is set to 2.6 with a loss tangent of 0.001 and the permittivity of InP is 12.5 having the same loss tangent. In the THz band, the high resistivity silicon suffers from almost no dielectric losses, so we used a lossless silicon material in our model with a permittivity of 11.9.

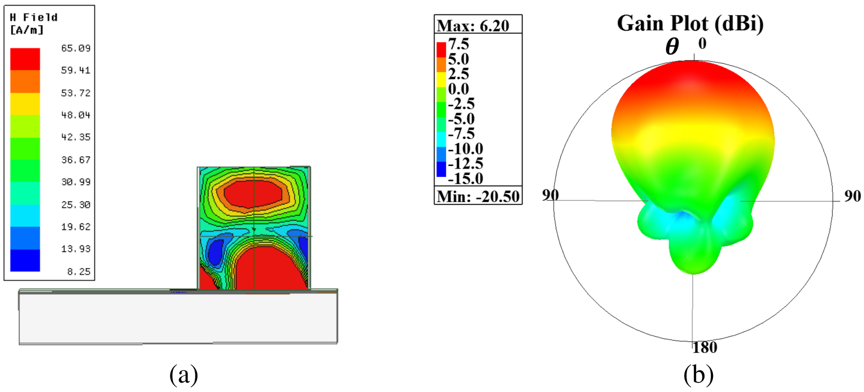

Figure 3. (a) receiver antenna (RA) performance at 100 GHz with the corresponding magnetic field distribution in the Si block; (b) radiation pattern.

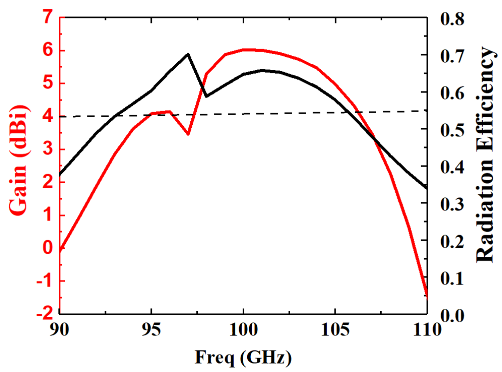

Figure 4. The frequency response of the receiver antenna (RA) gain and radiation efficiency between 90–110 GHz.

From Fig. 3(a) we can see that the designed RA performs like a dielectric resonator antenna. A higher order mode $TE_{\delta,1,3}$is excited at 100 GHz. The RA achieves a maximum gain of 6.2 dBi gain at 100 GHz in the desired direction of $\theta = 0°$ as shown in Fig. 3(b). While ignoring the port impedance mismatch, the RA gain yield a frequency bandwidth in the range of 93–107 GHz for values above 4 dBi with a radiation efficiency better than 55% (cf. Fig. 4).

In the 300 GHz band, because of the high dielectric constant of the InP substrate, most of the power will preferably radiate into the substrate. In order to suppress the surface wave and improve the gain of the TA, we add a 1 mm radius hemispherical Silicon lens at the backside of the InP substrate as displayed in Fig. 5(a). Fig. 5(b) shows the TA radiation pattern for the TA with the Si lens at 300 GHz. It can be seen that the TA achieves a significantly improved maximum gain of 14 dBi at 300 GHz and a radiation direction of $\theta = 180°$, which is exactly opposite to the RA. Fig. 6 shows the frequency response of the antenna gain at $\theta = 180°$ within a frequency range of 270–330 GHz, both with and without the lens, respectively. We observe that the lens levers the TA gain

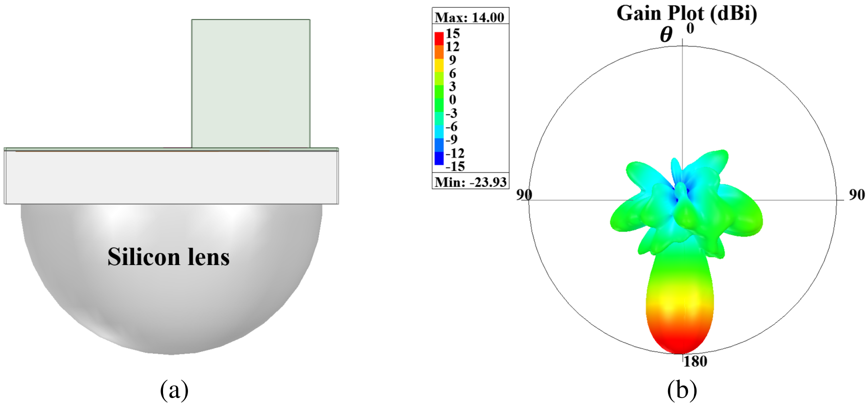

Figure 5. (a) configuration of the transmitarray element (TE). with a 1 mm radius Si lens and (b) the far field radiation pattern at 300 GHz.

and yielding in addition smoother gain fluctuations, which may be associated to weaker substrate mode excitation. Hence, in case of a missing lens, the TA behaves similar to a dielectric resonator antenna due to interfering substrate modes. Although it achieves a high gain at certain frequencies, the bandwidth remained very narrow. Fig. 7 shows the transmission parameter between the ports P1 and P2 (i.e., S_{21}) at two operating frequency bands. At around 100 GHz, the transmission loss amounts to 1.5 dB, while rising to above 15 dB within the 300 GHz band, which indicates that the received SIS can pass through the TA part whereas the FOS will not be transmitted into the RA.

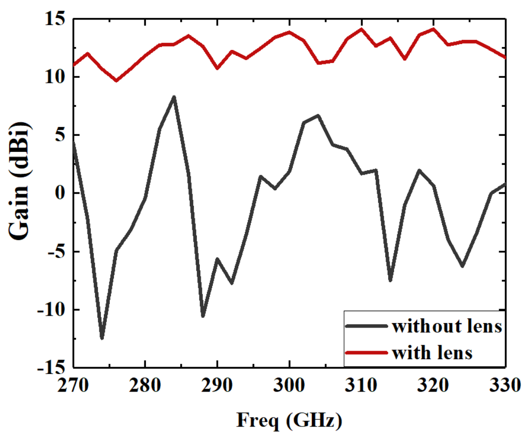

Figure 6. The frequency response of the transmitter antenna (TA) gain with and without lens.

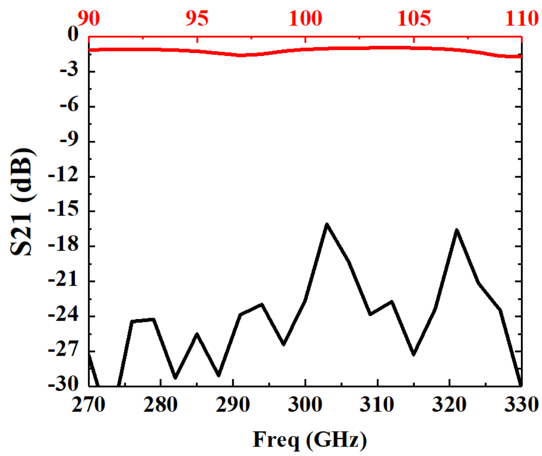

Figure 7. Frequency response of S_{21} related to the ports P1 and P2 of the transmitter antenna (TA) for the two operating frequency bands showing the desired band stop (black curve) and band pass (red curve) phenomenon.

3. CONCLUSION

A transmitarray element (TE) for a TB RTD oscillator with wireless subharmonic injection locking has been designed. The TE radiates the 300 GHz FOS and receives the 100 GHz SIS at exactly opposite directions. The simulation results shows that the gain of the TE is higher than 4 dBi within the SIS frequency range of 93–107 GHz with over 55% radiation efficiency. This gain increases to above 13 dBi around 300 GHz when applying a 1 mm radius silicon lens. The TA part can effectively suppress the transmission of the FOS into the RA and pass the received SIS into the TB RTD oscillator.

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REFERENCES

1. Akyildiz, I. F., J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Phys. Commun-AMST.*, Vol. 12, No. 4, 16–32, Feb. 2014.
2. Hillger, P., J. Grzyb, R. Jain, and U. R. Pfeiffer, "Terahertz imaging and sensing applications with silicon-based technologies," *IEEE Trans. THz Sci. Technol.*, Vol. 9, No. 1, 1–19, Jan. 2019.
3. Maekawa, T., H. Kanaya, S. Suzuki, and M. Asada, "Oscillation up to 1.92 THz in resonant tunneling diode by reduced conduction loss," *Appl. Phys. Express*, Vol. 9, No. 2, 24101, 2016.
4. Keller, G., A. Tchegho, B. Münstermann, W. Prost, F. Tegude, and M. Suhara, "Triple barrier resonant tunneling diodes for microwave signal generation and detection," *Proc 2013 European Microwave integrated Circuits Conference (EuMIC)*, 228–231, Oct. 2013.
5. Zhang, X., X. Zhou, B. Aliener, and A. S. Daryoush, "A study of subharmonic injection locking for local oscillators," *IEEE Microw. Guided Wave Lett.*, Vol. 2, No. 3, 97–99, Mar. 1992.
6. Zhang, X., X. Zhou, and A. S. Daryoush, "A theoretical and experimental study of the noise behavior of subharmonically injection locked local oscillators," *IEEE Trans. Microw. Theory Techn.*, Vol. 40, No. 5, 895–902, May 1992.
7. Arzi, K., G. Keller, A. Rennings, D. Erni, F. Tegude, and W. Prost, "Frequency locking of a free running resonant tunneling diode oscillator by wire-less sub-harmonic injection locking," *Proc. 10th U.K.-Eur.-China Workshop Millimetre Waves Terahertz Technol. (UCMMT)*, 1–4, Sep. 2017.
8. Jameson, S., E. Halpern, and E. Socher, "Sub-harmonic wireless injection locking of a THz CMOS chip array," *IEEE RFIC Symp. Tech. Dig.*, 115–118, May 2015.
9. Sun, Y. X. and A. Babakhani, "A wirelessly powered injection-locked oscillator with on-chip antennas in 180 nm SOI CMOS," *IEEE MTT-S Int. Microw. Symp. Dig.*, 1–3, May 2016.
10. Zhang, M., S. Clochiatti, A. Rennings, K. Arzi, W. Prost, N. Weimann, and D. Erni, "Antenna design for subharmonic injection-locked triple barrier RTD oscillator in the 300 GHz band," *2nd Int. Workhsop on Mobile THz Systems (IWMTS 2019)*, Jul. 2019.

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