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# Photonic-electronic IC of a subterahertz GaAs-on-Si in-phase/quadrature mixer

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**Abstract.** In this work, we propose a photonic-electronic integrated circuit of a 140 GHz in-phase/quadrature (I/Q) mixer based on the GaAs-on-Si platform which is in demand of next-generation wireless networks. The mixer conversion loss is ultimately limited by the on-chip power distribution network, exhibiting 7–8 dB insertion losses for the local oscillator and carrier signals with reflection losses as low as 28 dB. The circuit potentially ensures baud rates of up to 30 GHz which can be tuned. Although, the proposed integrated circuit is designed for operation at 140–150 GHz, it can be easily scaled-down for carrier frequencies of 280–300 GHz or even significantly higher. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

**Keywords:** subterahertz, Si integrated photonics, GaAs diode, I/Q mixer, 6G communication

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# Фотонно-электронная ИС субтерагерцового I/Q смесителя на основе GaAs-на-Si

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**Аннотация.** В данной работе предлагается фотонно-электронная интегральная схема I/Q смесителя для частоты 140 ГГц на основе GaAs-на-Si. Потери преобразования в смесителе ограничены встроенной сетью распределения мощности, которая обеспечивает вносимые потери сигналов гетеродина и несущей на уровне 7–8 дБ при потерях на отражение до 28 дБ. Предлагаемая интегральная схема рассчитана на работу в диапазоне 140–150 ГГц, но ее можно масштабировать для несущих частот 280–300 ГГц и даже выше.

**Ключевые слова:** субтерагерц, Si интегральная фотоника, GaAs диод, I/Q смеситель, связь 6G

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## Introduction

Communication technologies have become an integral part of human daily life. Their capabilities continue to grow steadily in response to society’s needs for new services and applications. State-of-the-art fifth-generation networks and systems are to be replaced by even more capable sixth-generation (6G) technologies in the foreseeable future. The allocated frequency bands for 6G wireless channels are partly above 100 GHz which potentially enables the use of both conventional and radio photonic approaches for the carrier signal generation and processing [1, 2]. Given the heritage of conventional quadrature amplitude modulation schemes in microwave wireless channels, they should be incorporated naturally into future 6G wireless systems. Thus, subterahertz (sub-THz) coherent frequency conversion devices for efficient signal modulation and demodulation at far-beyond-gigahertz baud rates are in demand. In this work, we propose a photonic-electronic integrated circuit (IC) of a sub-THz in-phase/quadrature (I/Q) mixer based on the GaAs-on-Si platform.

## Materials and Methods

Fig. 1, *a* provides a three-dimensional (3D) schematic of the proposed I/Q mixer along with field patterns in its structural elements simulated at $f$ = 140 GHz. The simulations rely on a numerical S-parameter analysis similar to that reported by us earlier in [3]. The developed Si power distribution network (PDN) has a fixed waveguide cross-section of $0.29\lambda_0 \times 0.23\lambda_0$ (width × height) and radii of curvature of $0.69\lambda_0$ in all circular segments with $\lambda_0$ denoting free-space wavelength of a guided wave. The PDN comprises straight waveguide sections adjacent to the Y-junction of the local oscillator (LO) input. They have optical lengths of $L_I$ and $L_Q$ that can be tuned to implement a precise 90° delay for quadrature up- and down-conversions at the desired frequency. The bottleneck in the proposed design is the conversion of the energy of the sub-THz waves propagating in the Si PDN into alternating currents in the GaAs planar Schottky diodes [4]. This is achieved at the PDN sections with diode-loaded metallic tapered slot lines (TSLs). The sections are terminated by distributed Bragg reflectors (DBRs) to enhance the conversion. The proposed GaAs-on-Si design is compatible with the quasi-vertical Schottky diode technology [5].

The performed preliminary numerical analysis at 140 GHz yields overall insertion losses for the LO and carrier signal input lines of 7–8 dB, with 6 dB power-splitting losses in Si PDN and 1.5 dB intrinsic to the transitions between single-mode waveguides of Si PDN and diode-loaded Ti/Au TSLs (see -S31, Fig. 1, *b*). The corresponding reflection losses are as low as 28 dB at the sub-THz LO port, and the isolation for the LO+carrier ports exceeds 13–16 dB. The developed PDN-to-diode transition provides an input frequency range of 135–145 GHz, which corresponds to a fractional bandwidth of 7%. In this range and at $L_Q - L_I = 0.16\lambda_0$, the 90° optical delay line ensures phase accuracy of 89±5° for quadrature conversion with amplitude imbalance up to 1 dB.

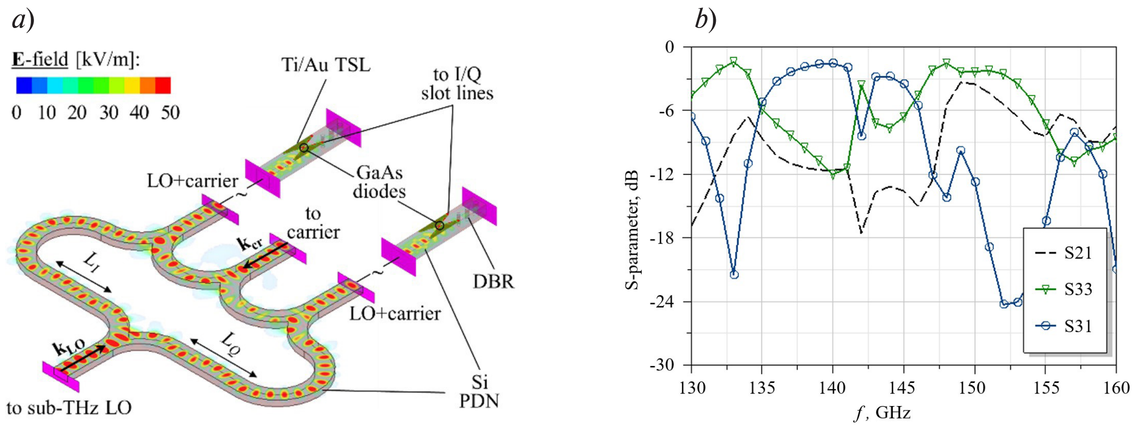


Fig. 1. 3D schematic of a 140 GHz I/Q mixer with a ribbon Si PDN (*a*), $\mathbf{k}_{LO}$ and $\mathbf{k}_{cr}$ are the wave vectors for LO and carrier signals and all abbreviations are denoted in the main text; scattering parameters of the PDN-to-diode transition (*b*), the PDN/TSL interface is represented by wave port 1, the DBR/free-space interface by wave port 2, the diode by lumped port 3

As a proof of concept, prototype of the device was manufactured in cleanroom process. The PDN with hexagonal lattice of openings with diameter of 100 μm and lattice constant 135 μm was performed in 450 μm-thick Si wafer via BOSCH-process. To protect the elements of PDN during etching process the 20 nm-thick aluminum mask was preliminary performed using maskless photolithography in lift-off process. As final step the residual aluminum mask was removed in wet KOH etchant. The deviation of linear dimensions of the device does not exceed 6%. Fig. 2, *a* provides photo of the prototype installed in measuring setup.

## Results and Discussion

We developed the measurement setup as follows. The microwave synthesizer equipped with the 12×frequency multiplier is used as a source of signal providing 130–160 GHz frequency range. In order to measure the insertion losses of the carrier signal input lines of the developed PDN, the output of the source is connected through the main line of directional coupler to the PDN's port 3 as shown in Fig. 2, *a*. The power meter (PM) equipped with the data acquisition system (DAQ) is consequently connected to ports 1 and 2, while the remaining two ports of the PDN are loaded by matched loads. When measuring the return losses for ports 1 and 2, the DAQ-equipped PM is connected through the coupled line of directional coupler. The measured S-parameters are presented in Fig. 2, *b*. As one can clearly see, the optimum operation frequency is 147 GHz, where

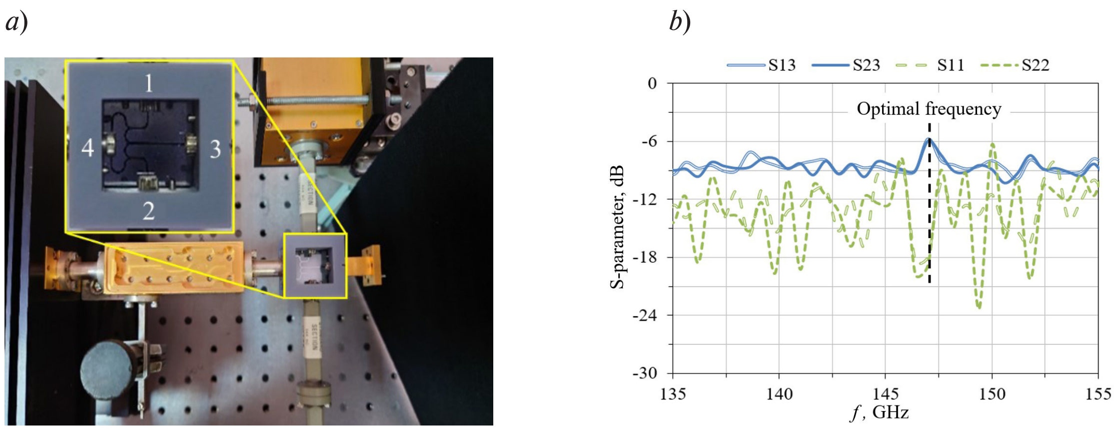


Fig. 2. Photo of the manufactured PDN with numerated ports in a measuring setup (*a*), ports 1 and 2 are outputs/inputs for the combined LO+carrier/the multiplied LO×I and LO×Q signals, ports 3 is the carrier signal input/output, and port 4 is the LO input; measured S-parameters of the PDN (*b*)

the measured insertion and return losses are equal to 6 dB and 18–20 dB, respectively. The LO input lines of the developed PDN exhibit bigger measured insertion losses, narrower operational bandwidth, but their accurate extraction requires further enhancement of the sampler holder.

The mixer design as it is ensures a baud rate of up to 25–30 GHz which is limited by the use of coaxial-to-planar interfaces in the I/Q signal input lines and low-inertial GaAs diodes [6]. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

## Conclusion

We propose a photonic-electronic IC of a sub-THz I/Q mixer compatible with the GaAsonSi platform. Mixer conversion losses are ultimately limited by the embedded power distribution network, exhibiting 6 dB insertion losses for the local oscillator and carrier signals (excluding 1.5 dB intrinsic to the transitions between Si waveguide and nonlinear lumped elements) with reflection losses approaching 20 dB. The mixer design ensures a baud rate of up to 25–30 GHz which is currently limited by the use of coaxial-to-planar interfaces in the I/Q signal input lines. This, however, can be further improved if the terminators at the rear end of the distributed Bragg reflectors for enhanced coupling of the mixing elements are revised. Moreover, the proposed IC is designed for operation at 140–150 GHz, but can be easily scaled-down for carrier frequencies of 280–300 GHz or even significantly higher. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

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