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INTERMEDIATE FREQUENCY CIRCUIT COMPONENTS FOR INTEGRATION OF ON-CHIP AMPLIFIER WITH THz DETECTORS

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Abstract

The demand for THz detectors for beam diagnosis and alignment at THz generating accelerator facilities increases continuously especially for room temperature applications. The Zero-Bias Schottky Diode (ZBSD) and field effect transistor (TeraFET) based Terahertz (THz) detectors are well suited for both, signal power detection at DC as well as Pulse shape diagnostics by down-conversion at intermediate frequencies (IF). The limited signal strength due to the roll-off factor of the low pass filter characteristic of the detectors at higher THz frequencies requires wide-band amplifiers to enhance the IF signal from a few µW to nW well above the noise floor of the subsequent post detection electronics. Using external amplifiers would enhance the signal losses even further due to additional connectors and rf-cable losses and degrade the signal to noise ratio (SNR). In order to maximize the SNR, we propose to have an on-chip amplifier integrated in the detectors intermediate frequency (IF) circuit in the same housing. In this work, we present the design and parametric analysis of components for transition to an IF circuit, which will be integrated in the ZBSD and TeraFET on chip with amplifier. A rigorous design analysis has been done to find the optimal parameters for wide-band operation in order to enhance the detector's resolution to capture pulses in the pico-second range with the help of fast post detection electronics.

INTRODUCTION

Research and development of materials and components in the Terahertz (THz) domain has been done rigorously since last couple of decades in order to explore this part of electromagnetic spectrum [1–3]. Due its excellent characteristics, the THz domain has numerous applications such as in imaging, spectroscopy, quality control, security, medical industry, astronomy, communications, energy and matter research, beam diagnostics and alignment at accelerator facilities, etc. [3]. The increasing demand for using this frequency spectrum has led the scientists to develop THz sources and detectors in this operable range. Room-temperature THz detectors developed in Refs. [4–6] are proved to be a cutting-edge technology for detector applications in THz domain. The detector itself is composed of both active and passive part. The active part consists of a semiconductor device such as Field Effect Transistors (TeraFET), Zero-Bias Schottky Diode (ZBSD), etc. The passive part is composed of all passive components which are used for connecting active to RF connector and later on post-detection electronics. The TeraFET or ZBSD rectifies the THz signal coupled through a silicon lens and is further down-converted from THz to millimeter frequency range [1]. The received signal is typically feed to the post detection electronics by using the intermediate frequency circuit (IF). For the detection of pico-second range pulses, it is necessary to increase the IF bandwidth components in the IF circuit as well as impedance matched circuitry to harness the full potential of the detectors [7]. Considering the important requirement for the optimization of the detector IF circuitry, in this paper we present the transition and ultra-broadband planar power divider (UBPPD) components which will be used for integrating the amplifier on-chip together with active devices in a same housing. The transition structures and UBPPD are investigated using 3D electromagnetic field simulation software (CST).

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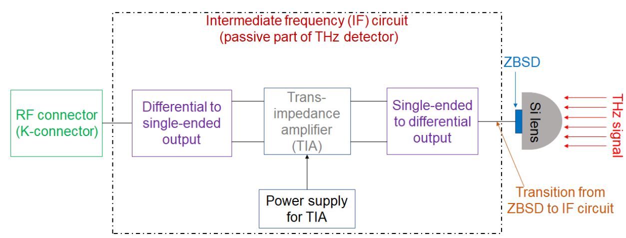

Figure 1: Block diagram of the THz detector.

TRANSMISSION LINES AS TRANSITION STRUCTURES

The block diagram of THz detector circuit is shown in Fig. 1. The blocks inside the dotted box represents the intermediate frequency (IF) circuit. The THz signal incident on the silicon lens is coupled to Zero-Bias Schottky Diode (ZBSD), which is mounted on the back side of the silicon lens (depicted as blue colour in Fig. 1.). A planar power divider along with a broadband phase shifter will be used to convert the rectified signal from single-ended to the differential input of the Trans-impedance amplifier (TIA). The output of the IF circuit is fetched to the read-out electronics via an RF connector (K-connector in this case as our target is to optimize detector initially until 40 GHz).

Figure 2 shows the transmission lines from TeraFET or ZBSD to the IF circuit. The dimensions of these structures are calculated according to Refs. [8,9]. Four different types of transmission lines such as coupled micro-strip lines (Fig. 2 (a)), co-planar wave-guide with only signal on top (Fig. 2 (b)), co-planar wave-guide (Fig. 2 (c)) and micro-strip line (Fig. 2 (d)) is investigated. All transmission line structures are simulated on a thin-film substrate with a thickness

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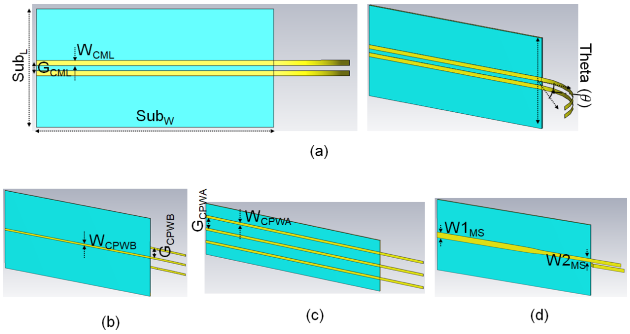

Figure 2: Investigated transition structures from active device (ZBSD) to IF circuit (a) Microstrip coupled lines, (b) Co-planar wave guide (CPW) as signal on top, (c) Co-planar wave guide (CPW) as all three ground-signal-ground on top and (d) Micro-strip line.

of 4.5 µm and a dielectric constant of $|\varepsilon|$ of 2.8. Table 1 shows the abbreviations meaning and dimensions of the structures shown in Fig. 2.

Table 1: Dimensions of the Transition Structures

Abbreviation	Full form	Dimension [mm]
G_{CML}	Gap between co-planar micro-strip lines	0.011
$GCPW_A$	Gap for CPW type A	0.050
$GCPW_B$	Gap for CPW type B	0.012
Sub_H	Substrate height	0.0045
Sub_L	Substrate length	0.25
Sub_W	Substrate width	1
W_{CML}	Width of co-planar micro-strip line	0.011
W_{CPWA}	Width of CPW A	0.012
W_{CPWB}	Width of CPW B	0.012
$W1_{MS}$	Width of micro-strip line	0.020
$W2_{MS}$	Width of micro-strip line tapered	0.012

The flexibility of having more degree of freedom while having transition from ZBSD or TeraFET to IF circuit gives an upper limit for the orientation of the other components. Therefore to understand the effect of bending (θ) the transition structures, we studied this effect on coupled micro-strip lines as shown in Fig. 3. The return loss (RL) is given as [8]:

$$RL(dB) = -20 \cdot log|\Gamma| \,, \tag{1}$$

where $|\Gamma|$ is voltage reflection coefficient. The transmission coefficient (T) and insertion loss (IL) is given by [8]:

$$T = 1 + \Gamma \tag{2}$$

$$IL(dB) = -20 \cdot log|T| \,. \tag{3}$$

Theta (θ) is varied from 0 to 90°. Figure3 (a) shows the transmission variation versus frequency. It is observed that at lower frequencies (below 10 GHz) the variation of (θ) doesn't have a significant effect, however between 30 to 40 GHz, ($\theta = 0°$) have less transmission as compared to the other variable (θ). While observing the phase (Fig. 3 (b)), it varies linearly along the frequency for coupled micro-strip line.

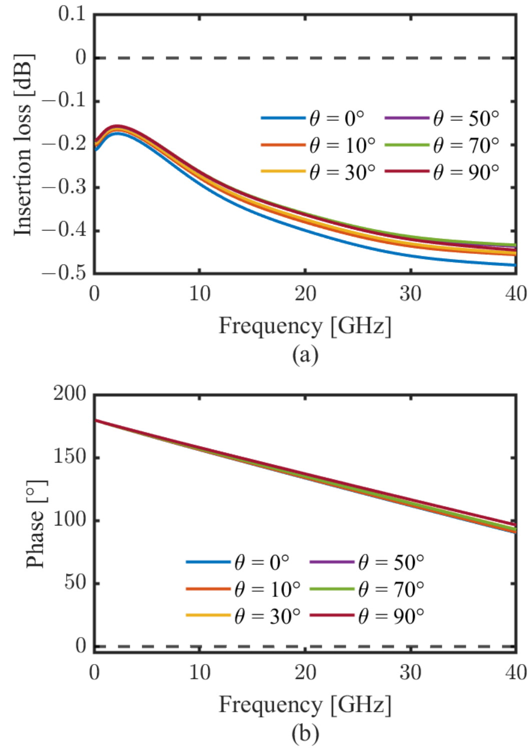

Figure 3: Study of varying θ on performance of coupled micro-strip line (a) Insertion loss over the frequency and (b) Variation of phase over the frequency.

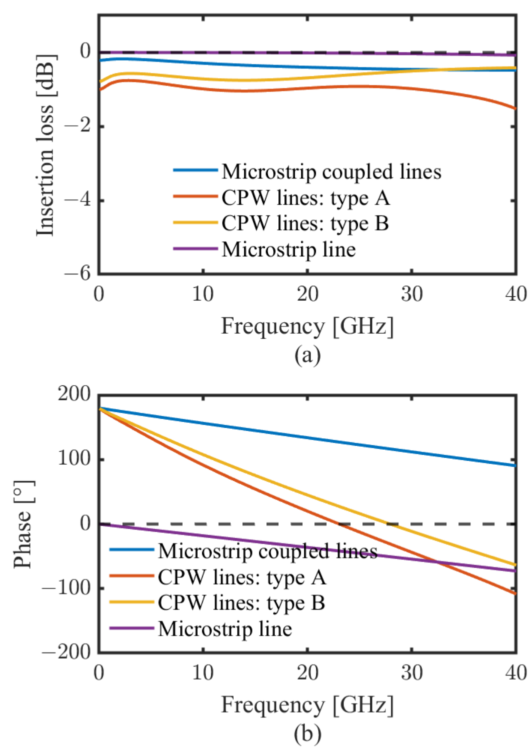

Figure 4: Comparison of different types of transition for a bending angle θ is 0°.

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Figure 4 shows the comparison of all four transition structures. The CPW based structures A and B have −1 dB IL over the whole frequency range (Fig. 4 (a)) but having a zero-phase crossing at ~25 GHz (Fig. 4 (b)). For micro-strip and coupled micro-strip lines no zero-phase crossing is observed and at the same time IL is −0.5 dB. The results propose that micro-strip lines are the optimum solution as a transition structures in this specific case.

ULTRA-BROADBAND PLANAR POWER DIVIDER (UBPPD)

A power divider sub-divides the power either equally or unequally [8, 10, 11]. For the development of compact THz detectors we need an ultra-broadband planar power divider (UBPPD) in order to divide the power equally in two arms (represented by block single-ended to differential output in Fig. 1), which will be further phase shifted by using a 180° phase shifter.

Figure 5 shows the investigated ultra-broadband planar power divider (UBPPD). The capacitively or inductively loaded concept of transmission line has been used (Fig. 5 (a)) here to reduce the circuit size and increase bandwidth. This lead to increase of capacitance or inductance per unit length, which ultimately lead to slower wave propagation because of decrease in phase velocity. Figure5 (b) shows the sketch of two sections of UBPPD.

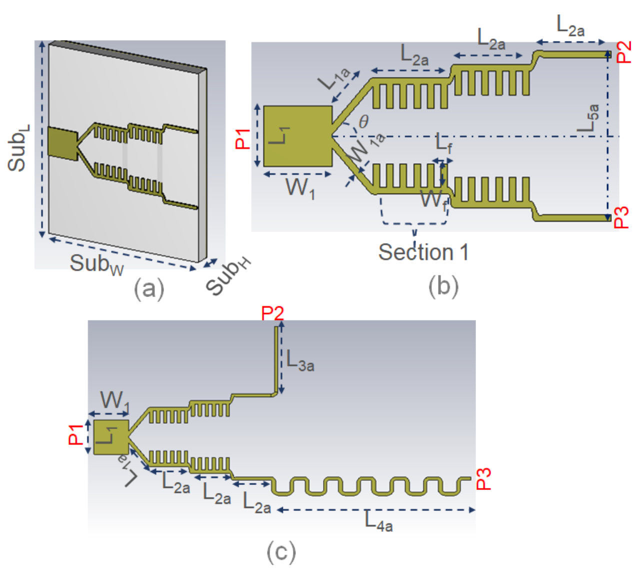

Figure 5: Ultra-broadband planar power divider (UBPPD) (a) Block diagram of UBPPD with substrate RO4350B Lo-Pro, (b) Sketch of two section UBPPD and (c) Sketch of UBPPD with phase delay and shift transmission lines.

All the abbreviations in the Fig. 5 are show in Table 2 with there respective values used for investigation. The structure was investigated on RO4350B LoPro.

The angle between the two arms (θ) plays an important role in UBPPD performance. Fig. 6 (a) shows the effect of varying the θ on UBPPD performance. Clearly $\theta = 55°$ is have better $|S_{11}|$ results compared two $\theta = 35°$ and $\theta = 45°$.

Table 2: Dimensions of UBPPD Structure

Abbre-viation	Full form	Dimension [mm]
L_f	Length of the finger	0.05
L_1	Length signal coupling pad	0.45
L_{1a}	Length of transition arm	0.44
L_{2a}	Length of single section	0.57
L_{3a}	Length of power divided arm for phase shifter	0.95
L_{4a}	Length of power divided arm for phase shifter with meander line	2.9
L_{5a}	Distance between two out ports P2 and P3	1.26
Sub_H	Substrate height	0.25
Sub_L	Substrate length	3
Sub_W	Substrate width	2.5
W_f	Width of a finger	0.18
W_1	Width of signal coupling pad	0.50
W_{1a}	Width of transition arm	0.060

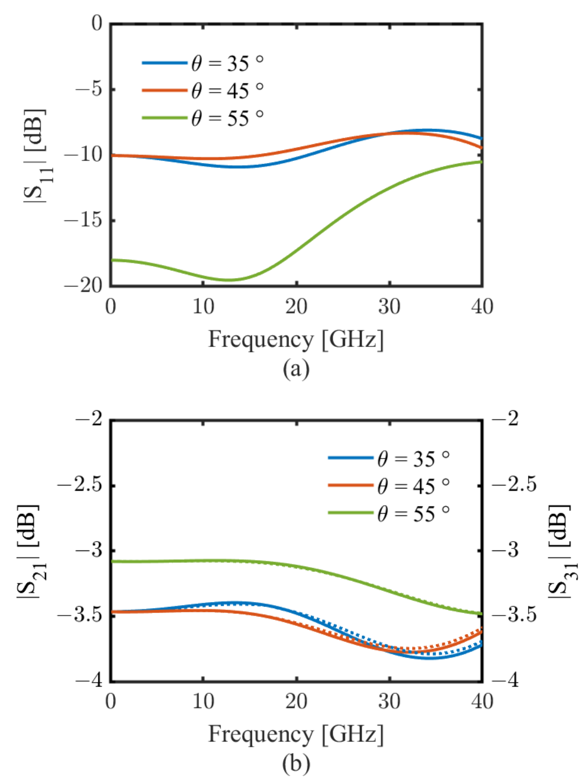

Figure 6: (a) Effect of varying (θ) on $|S_{11}|$ and (b) Effect of varying (θ) on $|S_{21}|$ and $|S_{31}|$.

Ideal power divider should have $|S_{21}| = |S_{31}|$ and as shown in Fig. 6 (b), the UBPPD have $|S_{21}| \approx |S_{31}|$ and quite stable over the whole frequency range. These varying (θ) investigation was performed for two section UBPPD (Fig. 5 (b)).

The proposed UBPPD was investigated for different sections (each section is 0.57 mm long). Figure 7 shows the performance of 3 different UBPPD having 2, 4 and 6 sections.

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More sections in UBPPD means having a larger transmission line, which changes the electrical length of the signal and ultimately results in degrading the performance of the component. Amplitude unbalance is calculated by $|S_{31}| - |S_{21}|$ and the phase unbalance is calculated as $deg(S_{31}) - deg(S_{21})$. Figure 7 (a) shows the amplitude unbalance for 2, 4 and 6 section UBPPD. The 2 section structure have ±0.005 dB of unbalance and its comparatively stable over frequency, while for 4 section it is ±0.01 dB and ±0.02 dB for 6 sections UBPPD. Similar trend is observed for phase unbalance as well Fig. 7 (b). Therefore, its better to have 2 sections UBPPD for the IF circuit.

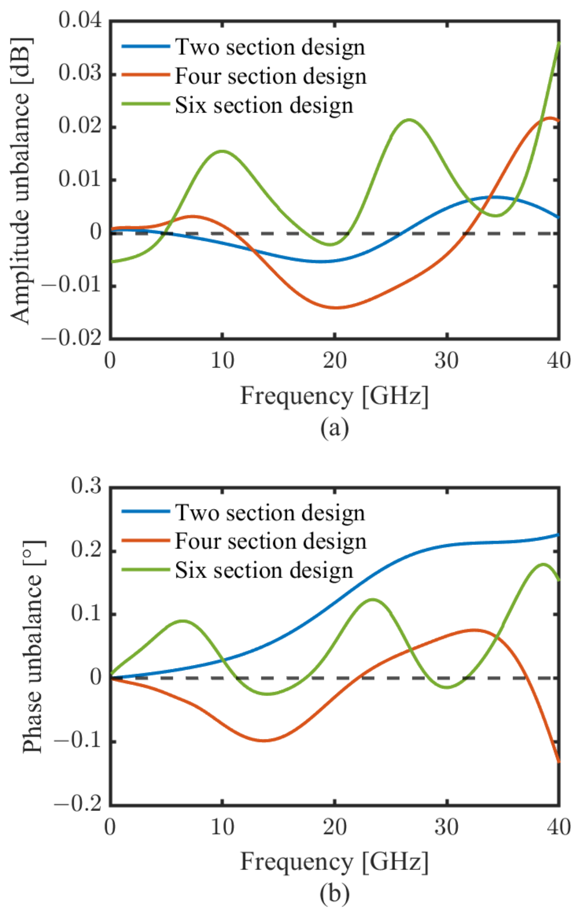

Figure 7: (a) Amplitude unbalance comparison for different sections and (b) Phase unbalance comparison for different sections.

As a pre-liminary study on using the phase shifter with UBPPD we investigated on meander shaped structures as shown in Fig. 5 (c). The meander shaped quarter-wavelength structure is used for the phase shifting as meander shaped structures leads to periodic variation of propagating signal and slow it down as the phase velocity decreases along it. The $|S_{11}|$ parameters are well below -10 dB until 40 GHz (Fig. 8 (a)) while the $|S_{21}|$ and $|S_{31}|$ have slightly bigger amplitude unbalance of ±2 dB (Fig. 8 (b)) and the phase unbalance is also significant along with flip at 15 GHz and 25 GHz as shown in Fig. 8 (c).

CONCLUSION

The transition from THz detecting device such as TeraFET and ZBSD to IF electronics is a crucial part for the overall detector optimization. The parameter study on the variation of bending the transition structures exhibits significant impact on the propagating signal. From four different investigated structures, we found that the micro-strip line may be the best option for a transition structures. The UBPPD is crucial to divide the power equally in two arms which will than be phase shifted by using a planar phase shifter (the investigation on broadband planar rogers substrate based 180° phase shifter is still under progress) and finally feed to the broadband amplifier. The investigated two section UBPPD is the optimal solution (considering rogers substrates) for the broadband phase shifter and will be fabricated by using photo-lithography process and clean room technologies.

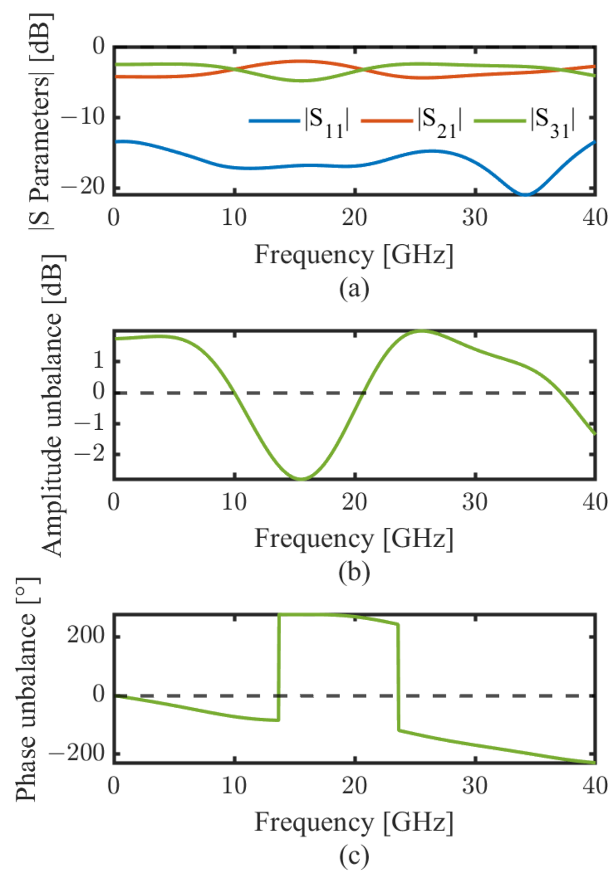

Figure 8: Two section UBPDD with meander phase shifter (a) S-parameters, (b) Amplitude unbalance and (c) Phase unbalance.

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