HORIZON 2020

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Design report of phase distribution PIC

Terahertz based Ultra High Bandwidth Wireless Access Networks

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Approved by:	PSC

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CO	Confidential, only for members of the consortium (including Commission Services)	

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Executive summary

This document provides the necessary information on the design for fabrication of a 4-channel phase distribution PIC. In particular it describes the design envisaged for enabling coupling with the UTC-PD antenna array and to provide the phase changes that are required.

A brief summary of the core specifications is presented followed by implementation specifications, requirements, details of the antennas such as pitch, waveguide geometry and electric field distribution of the optical mode at a wavelength of 1550 nm. After that, a table summarizing the design specifications is presented.

In the design section, a theoretical analysis is shown for arrays of antennas as well as the considerations that are required to implement delay lines in photonic integrated circuits. Based on said considerations several calculations are presented as well as a schematic representation of the functional system and a capture of the final layout.

1 Introduction

1.1 Summary

This deliverable contains the design of a phase distribution photonic integrated circuit (PIC) as it is required for fabrication. Such phase distribution system will be co-integrated with an array of UTC-PDs for the coherent transmission of radiation frequencies between 100 and 300 GHz and possibly reception of 300 GHz signals and will provide beam steering capabilities.

1st list of given specifications that the system must comply with.

2nd Theoretical analysis and simulation.

3rd Pre-design of selected optical components.

4th Size estimation of components and system.

1.2 Relationships with other deliverables

The design presented in this document relates to the following deliverables:

- D3.5 - M16:Dec2018 - Characterization report of phase distribution PIC.

1.3 Contributors

The following partners have contributed to this deliverable:

- UCL - Array of UTC-PDs and specifications.
- BAY Photonics - Layout feedback for future packaging.

2 System definition

2.1 Specifications

2.1.1 Evaluation

The TERAPOD project aims to provide the technology for future Data Centre ultra-fast wireless links. A crucial part of this approach is the capacity of such systems to find and establish links between devices. In order to optimise the performance and reduce the power consumption, TERAPOD is developing a beam forming system which allows efficient and low-power multi-device links by optically controlling the directionality of the antenna. Such optical control is based on photonic integrated circuits (PICs). The design of said PICs is described in section 3.2 of this report for an array of antenna elements.

2.1.2 Requirements

Layout of antenna element array:

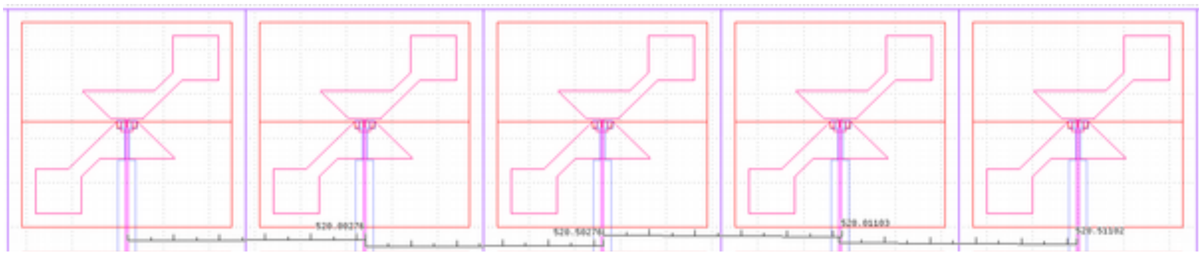


Figure 1: Array of antenna elements for radiation in the THz range

The pitch between the optical inputs of each antenna element is 520 µm. Figure 2 shows the electric field intensity distribution corresponding to the modal shape of the input waveguide at 1550 nm wavelength.

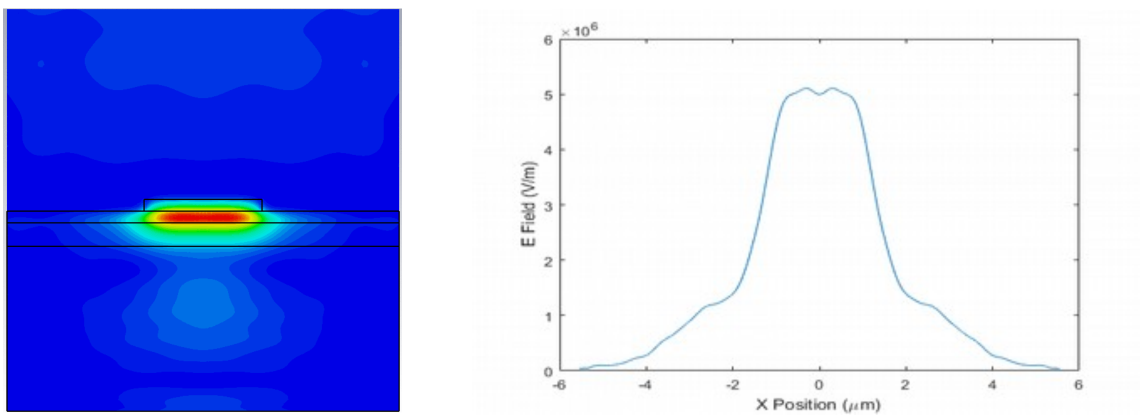


Figure 2: Left: 2D Electric field distribution in the InP waveguide (field normalized: blue for close to 0, red for close to 1). Right: Mode field diameter in the horizontal direction of the mode shown in the left.

The specified requirements are contained in the following table:

Antenna specifications	
Array Pitch	520 µm
1st Wavelength	1550.3 nm
1st Wavelength linewidth	40 kHz
2nd Wavelength (tunable)	1530-1560 nm
2nd Wavelength linewidth	500 kHz
MFD horizontal direction	8 µm

Design specifications		
Block	**Parameter**	**Value**
All design	Operational wavelength range	C-band (1.55 µm)
	Polarization	TE
Input Coupler	Input coupling loss	Down to ~3 dB
Variable 1x4 Splitter	Excess loss	< 2 dB
Amplitude and Phase variable	Modulator: Insertion Loss	< 3 dB
Array antennas	Radiation frequency	100 GHz
	Number antennas	4

2.2 Device Design

2.2.1 Theoretical analysis

The target radiated carrier frequency is 0.1 THz. This corresponds to a wavelength of about 3000 µm. Such signal is guided in the difference between the frequencies of two narrow linewidth lasers, both are then guided to the UTC-PDs where the THz signal is radiated.

By employing an array of antenna elements, it is possible to coherently add the radiated THz signal in a specific direction while suppressing undesired directions [1]. The radiation diagram (F) of the array is determined by the radiation diagram of the antenna element (F_e), the phase difference between antennas, the amplitude and the distance between antenna elements (FA), such that:

$$F = FA \cdot F_e$$

For the case of a linear array in the *x*-direction (transversal-horizontal to the propagating optical signal), the radiation diagram will be invariant in the *yz*-plane (angle θ=0). However, the radiation diagram can be varied in the xy-plane (angle θ=[0, π]) by changing the relative phase and amplitude of the optical signal that arrives to each antenna element.

Such antenna arrays can be described by the array factor ($|FA(\Psi)|$), where:

$$\Psi = kd\cos(\theta) + \alpha,$$

And being k the free space wavenumber, d the distance between antenna elements and α the phase difference between the input signals to each array element.

Depending on the amplitude distribution between antenna elements, the FA will provide a different radiation diagram:

Amplitude distribution		$\lvert FA(\Psi)\rvert$	First zero location	LMS (dB)
Linear	$\sum_{n=0}^{N-1} z^n$	$\frac{sin(N\,\Psi/2)}{sin(\Psi/2)}$	$2\,\pi/N$	13.4
Binomial	$\left(\sum_{n=0}^{\frac{N-1}{2}} z^n\right)^2$	$\left(\frac{sin((N+1)\,\Psi/4)}{sin(\Psi/2)}\right)^2$	$2\,(2\pi/(N+1))$	26.8
Triangular	$(1+z)^{(N-1)}$	$(2cos(\Psi/2))^{N-1}$	π	--

For the case of an array of 4 elements with d = 520 µm and linear distribution of amplitude, the radiation direction of the FA will vary as $\theta_{max} = acos(\alpha/kd)$. The following table shows the simulated radiation patterns as a function of the phase difference between radiating elements.

$\alpha = 0$ or $\Psi = kd\cos(\theta)$	$\alpha = kd$ or $\Psi = kd(1+\cos(\theta))$

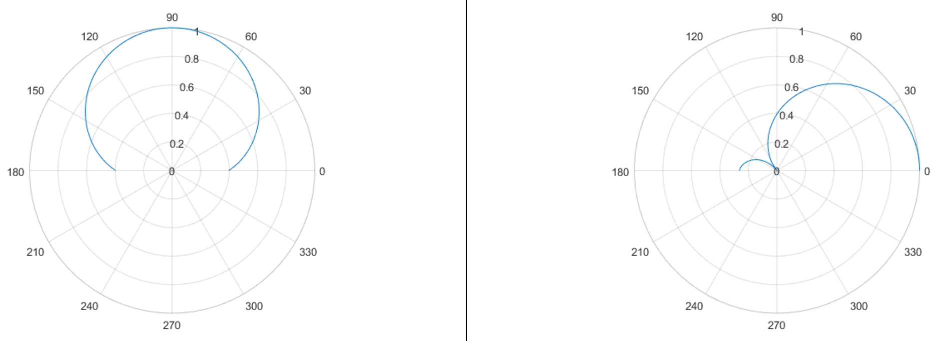


Figure 3: Simulated radiation patterns

2.2.2 Considerations

For the system described in section 3.2.1, the most extreme phase difference will be 3 times kd between the first and the last antenna. In order to provide 180° scan range, the tuneable phase difference must range from *0* to *6kd*.

In a PIC, this translates as a maximum phase difference of 6.535° which corresponds to a time delay of $t = 1.04\lambda/c = 10.41$ ps.

In a PIC, the time delay is obtained as

$$\tau = \frac{L * n_g}{c}$$

where τ is the time delay, L is the length of the photonic waveguide, c is the speed of light in vacuum and n_g is the group index of the guided light. The latter is defined by the waveguide geometry and the material. At λ = 1550 nm for a width of 1 µm, the group index is $n_g = 2.11676$.

By employing a standard phase shifter, a waveguide must be at least 190 cm long to provide the required delay. This translates to a waveguide of 1130 µm for a 10° range, easily accessible with Silicon Nitride waveguide technology.

The approach with straight delay lines is very limiting. However, in PIC-based technology it is possible to integrate resonant cavities as delay lines, providing a very wide delay tuning in the picoseconds range. Such resonant cavity has the form of a ring resonator.

Assuming a roundtrip loss of 0.5 dB, the delay (τ_g) provided by a ring at 1550 nm is given by the following table:

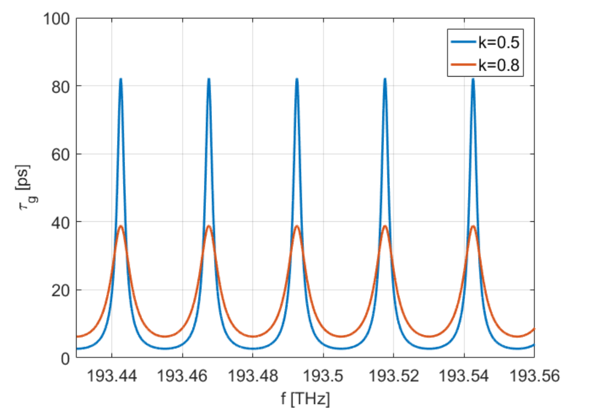
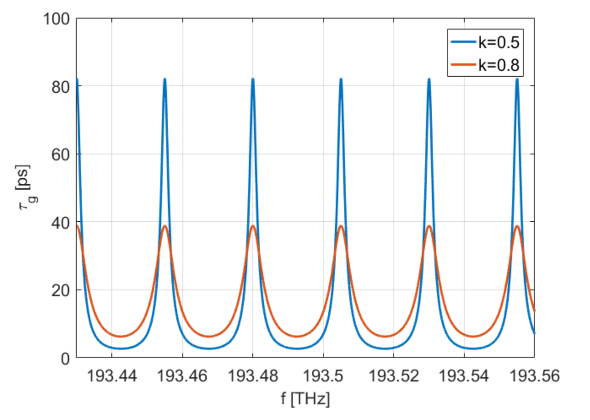
Heating OFF	Max. Heating ON
	

Figure 4: Delay as a function of frequency and heating

Such ring resonator, provides sufficient range to accurately delay the signal to each output antenna element such as the beam can be efficiently steered by at least +-45□.

2.2.3 PIC Design

The phase distribution system based on ring resonators can be synthesized as:

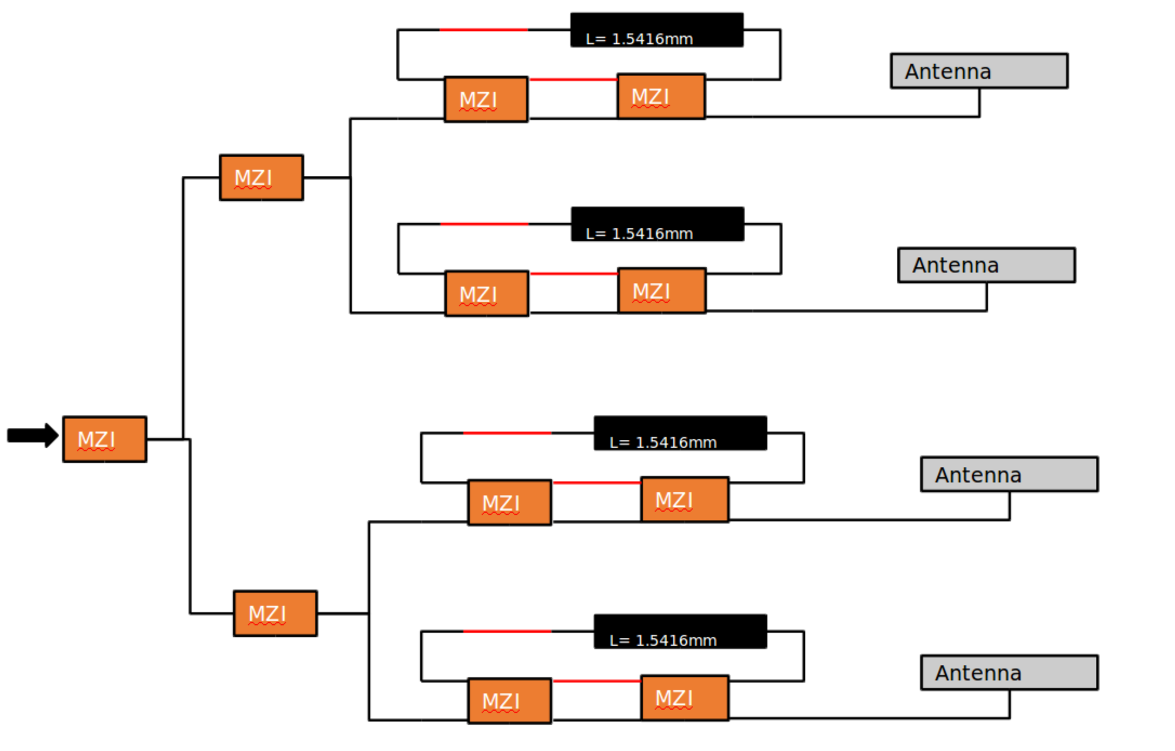


Figure 5 PIC phase distribution system

And the layout of such system is contained in the middle black box on the following layout design:

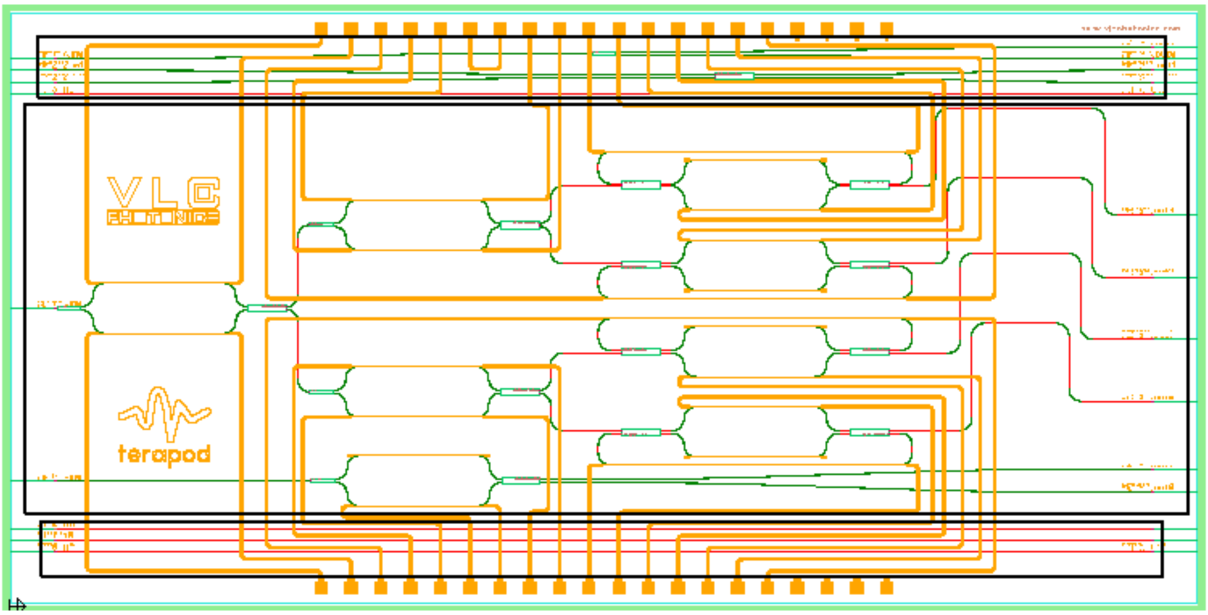


Figure 6: System mask layout

Here, in order to test the individual building blocks, these are individually contained in the top and bottom black boxes.

The layout also contains a metal layer made out of Aluminium, standard metallization layer compatible with CMOS manufacturing. The metal layer is required for the control of the beam steering by means of micro-heating elements. In order to ease the packaging, each element is wired towards the top or bottom edge of the layout and ended in a 100 µm² pad with a pitch of 250 µm.

3 Conclusion

4

With the presented configuration, it is possible to guide coherent radiation generated by two different lasers with a radiation frequency difference between 100 and 300 GHz. The guided radiation will be delayed and coupled to an array of InP antennas capable of radiating at frequencies around 300 GHz.

References

[1] M. Burla *et al.*, "Integrated Photonic-Band Beamformer Chip With Continuous Amplitude and Delay Control," in *IEEE Photonics Technology Letters*, vol. 25, no. 12, pp. 1145-1148, June15, 2013.