Wavelength-tunable true time delay for multi-beam radio beamformer in multi-Gbps satellite communication

Wavelength-tunable True Time Delay for Multi-beam Radio Beamformer in Multi-Gbps Satellite Communication

N. Tessema, Z. Cao, J.H.C. van Zantvoort, E. Tangdiongga, A.B. Smolders, A.M.J. Koonen

COBRA Research Institute, Eindhoven University of Technology, PO Box 513, 5600MB Eindhoven, The Netherlands, Email: n.tessema@tue.nl

Abstract *We present a Si_3N_4 photonic integrated chip providing wavelength-dependent true time delay for forming multiple radio beams: a number of multi-Gbps connections from home-to-multiple satellites can be supported simultaneously.*

Introduction

Radio beamforming is an ultimate solution to satisfy the increased bandwidth demand of wireless communication users. Electronic beamformers using traditional phase shifters have intrinsic narrowband characteristics. The realization of photonic integrated true time delay (TTD) devices is proven to be the ultimate solution for a wideband beamformer[1-3].

With the ever increasing demand for high capacity links, home-satellite communication is a key enabler technology for users located in remote areas. Home-to-multiple-satellite connections are highly beneficial since they enable users to simultaneously tune into a wide range of services such as TV, internet, mobile connections provided by different satellites. Currently, motorized dish alignment techniques are used to switch connections between satellites supporting a single satellite connection at a time. In order to setup multiple satellite connections simultaneously, the home user terminals need to deploy multi-beam radio beamforming. Fig. 1(a) shows such a home-satellite system with an optically-controlled radio beamformer. An antenna array mounted in the focal plane of a dish reflector, known as a focal plane array (FPA) is controlled by a TTD. We use *N* optical wavelengths in the TTD to create different delays for feeding the antenna arrays. In this way, *N* radio beams simultaneously point to *N* satellites. The beamforming in the FPA enables a higher gain than a traditional reflector antenna. Within a home network, an optical fibre link can be used to provide seamless wideband connectivity to the devices per room.

Several realizations of an optically-controlled multi-beam RF beamformers have been reported using wavelength-dependent TTD (WD-TTD) based on discrete components. Integrated Si_3N_4 optical ring resonator (ORR) test structures with WD-TTD bandwidth of 1 GHz were realized and characterized for multi-beamforming application as given in[3]. The design implemented a Vernier approach which involves cascading two or more ORRs with different free spectral range (FSRs). This configuration provides WD-TTD at the expense of increased device complexity.

In this paper, we present a novel approach in which only a single ORR is used to generate the WD-TTD with a bandwidth of 2 GHz. The measured delays can be used in the realization of multi-beam RF beamforming. Since only a single ORR per antenna element is used, the device complexity is reduced significantly. The works given in[2-3] did not show data transmission through TTD chip. In this paper, we present successful transmission of Nyquist-subcarrier multiplexed data through the TTD chip. The non-orthogonality in the Nyquist-subcarrier multiplexed signals (as opposed to an OFDM

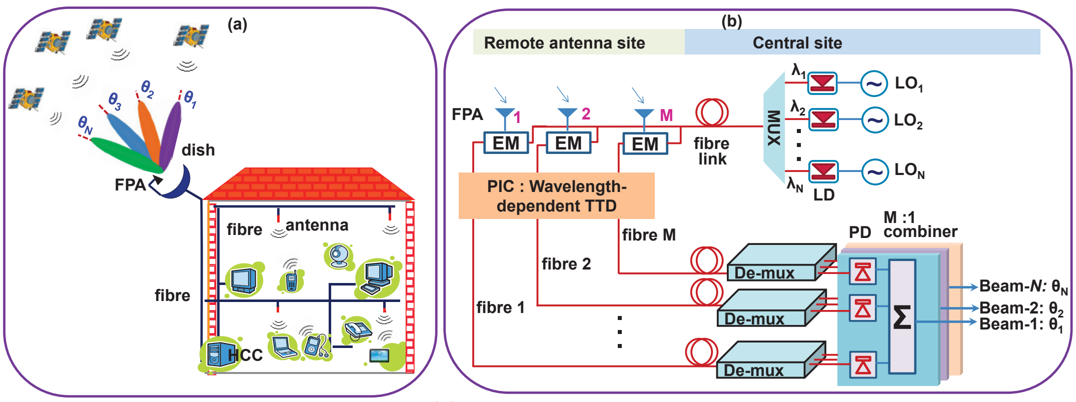

Fig. 1: (a) A home-to-multiple-satellite system (HCC: home communications controller) (b) optically-controlled multi-beam radio beamformer

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signals) is suitable for combating carrier synchronization offset in the satellite channels[4]. In addition, a reduced peak-to-average-power ratio can be achieved since the number of sub-carriers is not very large.

Operation Principle of an Optically-controlled multi-beam RF beamformer

The diagram in Fig. 1(b) illustrates a multi-beam radio beamformer which is controlled by a TTD implemented in a photonic integrated circuit (PIC). The remote antenna site and the central site are connected by a short fibre-link of less than 1000m. In the WD-TTD PIC, N wavelengths originating from N lasers are delayed differently. $N\times M$ delays are simultaneously generated by using M ORRs, where M is the number of antenna elements of the FPA. In this way, multiple radio beams can be steered simultaneously in the desired directions [θ_1, θ_2, …,θ_N]. We realized and characterized a WD-TTD PIC intended to operate in such a home-satellite system.

Wavelength dependent TTD

The realized TTD is a cascade of an optical side band filter (OSBF) and an ORR as shown in Fig. 2(a). The OSBF is designed for single side band filtering of radio frequency (RF) signals of 20 GHz and higher. It is provided with heaters *A, B,* and *C* which allow thermo-optic tuning of the OSBF response. Heater *D* of the ORR enables tuning of the resonance wavelength and heater *E* enables tuning the coupling ratio ϰ. Fig. 2(b) shows the theoretical plot of the group delay of the realized ORR under different coupling conditions. The wavelength delay tuning is done by placing the wavelengths [λ_1, λ_2… λ_N] in the ORR delay response as shown in Fig. 2(b). For lower coupling ratios, it is seen that the wavelength vs delay slope is significantly large, and a large delay variation happens in a narrow wavelength range. For higher coupling ratios of 0.5 and higher, the wavelength vs delay slope is significantly lower, and shows smaller delay

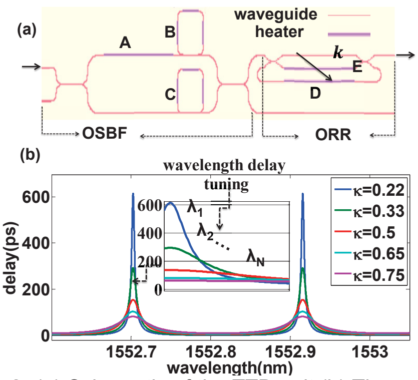


Fig. 2: (a) Schematic of the TTD unit (b) Theoretical group delay of an ORR: wavelength delay tuning

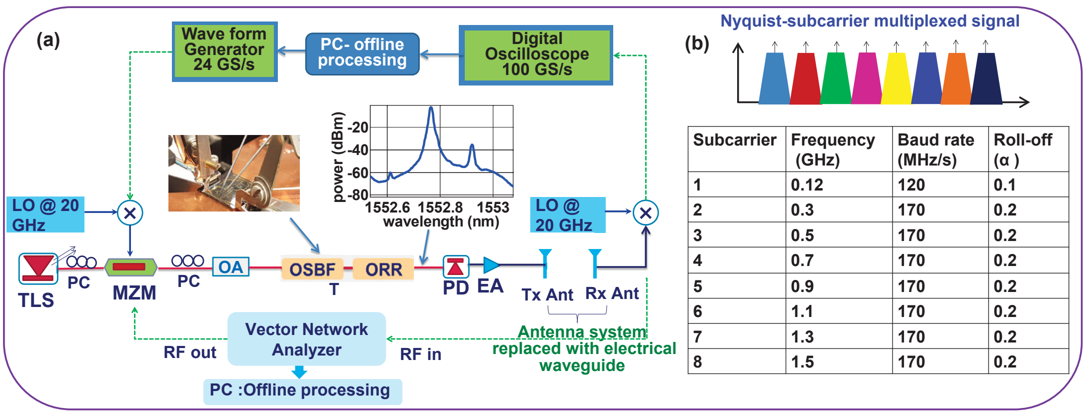
variation in a given wavelength range. The higher the slope, the narrower the TTD bandwidth. On the other hand, the higher the slope, the larger delay tuning range per unit wavelength. Therefore, the TTD bandwidth and the resulting delay variation per unit wavelength can be thermo-optically optimized by varying ϰ.

Experimental Setup

The experimental setup is given in Fig. 3 (a). The first part of the experiment involves measurement of the delay. A vector network analyser (VNA) is used to sweep an RF signal from 18 to 20 GHz, while the laser wavelength is incrementally tuned. The second part of the experiment involves the transmission of data signal through the optical chip at 20 GHz. Eight non-orthogonal subcarriers were modulated by a QAM-16 signal which is band-limited by a Nyquist filter. The roll-off factor α of the Nyquist filter was optimized per subcarrier. The guard band between the subcarriers is 30 MHz. The signal format is given in Fig. 3(b) and has a data rate of 5.2 Gbps. A fibre-chip-fibre insertion loss of 11 dB was measured.

Results and discussions

The phase response measurement for TTD bandwidth of 2 GHz is shown in Fig. 4(a). During the measurement, heater *E* voltage was tuned



Subcarrier	Frequency (GHz)	Baud rate (MHz/s)	Roll-off (α)
1	0.12	120	0.1
2	0.3	170	0.2
3	0.5	170	0.2
4	0.7	170	0.2
5	0.9	170	0.2
6	1.1	170	0.2
7	1.3	170	0.2
8	1.5	170	0.2

Fig. 3: (a) Experimental setup (b) Transmitted Nyquist-subcarrier multiplexed signal

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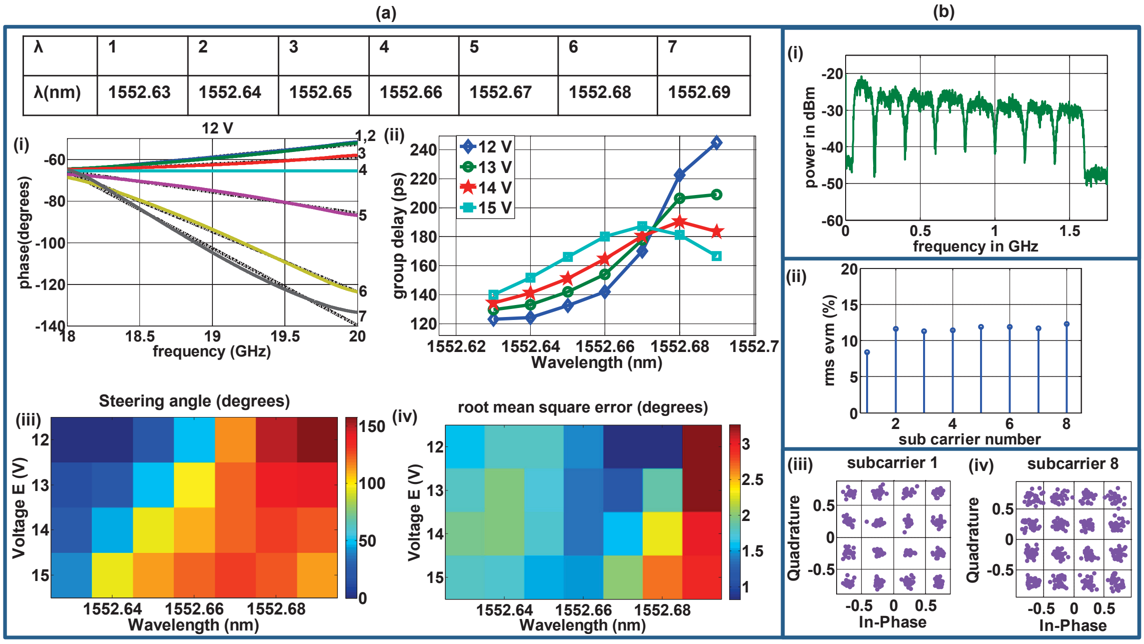

Fig. 4: (a) Phase measurement results (b) data transmission results

from 12 to 15 V, while the wavelength was tuned from 1552.63 nm to 1552.69 nm. The phase response at 12 V is shown in Fig. 4(a, i), in which the solid lines represent the measured phase responses and black dotted lines represent their best linear fits. The phase slope of the linear fits were used to obtain the group delays values. It can be seen from Fig. 4(a, ii) that by tuning the heater *E* voltage, thus tuning coupling ratio ϰ, results in different delay variation per unit wavelength. With 7 wavelengths and 4 thermo-optic voltage settings a total of 28 delays were measured which yield 28 steering angles as shown in Fig. 4(a, iii). The steering angles were calculated for a 2×1 beamformer at 20 GHz. It can be seen that steering angles from 0° to 158° can be realized. The measured delays can be employed to steer, *N* beams at the same time for a 1-by-*M* antenna array; (while N, M satisfy, *N*×*M*=28), and when *M* ORRs are used. The root mean square error (rmse) quantifies the deviation of the measured phase responses from the corresponding best linear fits and is given in Fig. 4(a, iv). The rmse values range from 0.8° - 4.6°. The smallest rmse corresponds to the smallest wavelength vs delay slope and the largest rmse corresponds to the largest wavelength vs delay slope. The impact of these phase errors on the beamformer performance is expected to be minimal. Fig. 4(b, i) shows the received Nyquist-subcarrier multiplexed signal. High-quality signal reception was achieved with a receive SNR of 20 dB per subcarrier. The 6 dB roll-off across signal bandwidth is the result of the impact of various RF components in the experimental setup. The rms error vector magnitude (evm) per subcarrier is given in Fig. 4(b, ii). The smallest evm of 8.4 % was measured at subcarrier 1 and the largest evm of 12.3% was measured at subcarrier 8. Clear constellation diagrams were obtained in both cases as shown in Fig. 4(b, iii) and Fig. 4(b, iv).

Conclusions

We have presented on-chip WD-TTD based on a single ORR that can potentially be employed in a multi-beam RF beamformer. Multiple beams can be used to provide broadband multi-satellite connections to users. A Nyquist-subcarrier multiplexed signal format suited for satellite communication has been employed to achieve 5.2 Gbps transmission capacity.

Acknowledgements

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References

[1] J. Campany et al., “Microwave Photonics combines two worlds,” Nat. Photonics, Vol. **12**, no. 5, p. 319 (2007).

[2] M. Burla et al., “Multiwavelength-Integrated Optical Beamformer based on Wavelength Division Multiplexing for 2D Phased Array Antennas,” J. Light wave Technol., Vol. **32**, no.20, p. 3509 (2014).

[3] L. Zhuang et al., “Novel low-loss waveguide delay lines using Vernier ring resonators for on-chip multi-λ microwave photonic signal processors,” Laser & Photon.Rev., Vol. **7**, no.10, p. 994(2013).

[4] J. Dommel et al., "5G in space: PHY-layer design for satellite communications using non-orthogonal multi-carrier transmission," *ASMS/SPSC*, Livorno (2014).

