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Silicon Nitride Integrated Optical Beamforming Network for Millimeter Wave Photonics Systems

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Abstract— This work presents the design of a 1x4 optical true time delay beamforming network integrated into a Si₃N₄ photonic chip for hybrid millimeter wave/photonic systems. The spectral periodicity of a ring resonator-based tree structure is exploited to provide simultaneously the same delay configuration to different gigabit optical channels, increasing the effective beamforming bandwidth. The free spectral range is fixed to 33.3 GHz to assure the combability with wavelength division multiplexing applications. The simulation results show that the progressive delay between outputs can be continuously tuned from 0 ps to 20 ps. These values assure the operation at 60 GHz band.

Keywords— Photonic integrated circuits, beam steering, millimeter wave communication, radio access networks.

I. INTRODUCTION

The enormous growth in the number of mobile devices and the continuous developing of bandwidth-intensive applications have posed a capacity challenge to existing wireless access networks. The solution to boost the capacity of wireless links is to move from the current overexploited spectrum regions (below 6 GHz) to the millimeter wave (mm-wave) bands (30 – 300 GHz) [1]. Among them, the main candidates to implement present and future standards (5G and IEEE 802.11) are Ka-band (26.5 – 40 GHz), V-band (40 – 75 GHz) and E-band (70 – 95 GHz) [2]. Photonic techniques offer some key advantages for mm-wave signal generation, including low loss, broadband nature and seamless integration into fiber optic networks. Hybrid mm-wave/photonic systems are ideally suited to implement next generation of radio access networks (RAN). They combine the advantages of both technologies: the high capacity of fibers to cover long distances and the flexibility of wireless communications to expand the network reach.

One of the major challenges of mm-wave frequencies is the tremendous path loss. This issue can be solved by using high gain directive antennas with beam steering capabilities. The phase configuration of a phased array antenna (PAA) can be settled by photonic techniques, meaning fully convergence with hybrid mm-wave/photonic systems. Furthermore, microwave photonic applications can be implemented by photonic integrated chips (PIC), offering additional advantages in terms of size cost and power consumption [3]. An integrated beamforming network have been already realized for K-band [4]. However, a system implementation, compatible with next generation standards, has not be fully addressed.

In this work, we report the design of an integrated tunable optical true time delay (OTTD) beamforming network full-compatible with a hybrid optical/mm-wave RAN. The operational principle of the chip is demonstrated simultaneously for different optical channels, which can be converted into the mm-wave domain by optical heterodyning [5]. As a result, several gigabit data streams can be potentially transmitted over 60 GHz band with the same delay configuration.

II. PROPOSED SYSTEM ARCHITECTURE

While conventional cellular access networks consist of several macro base stations, in which the signals are processed and transmitted to and from the mobile terminals, the centralized RAN (C-RAN) model proposes to move the signal processing and modulation to a central office (CO) which optically distribute the data to radio antenna units (RAUs). Therefore, RAUs are simplified, reducing the deployment cost of new stations. The densification of RAUs can also be achieved by using wireless interfaces to extend the reach of optical fibers.

Fig. 1 shows a C-RAN architecture combining optical and mm-wave links. In the CO, a continuous wave laser serves as a light source. Its frequency is tuned according to the 100 GHz frequency grid defined by ITU-T Recommendation G.694 to support dense wavelength division multiplexing (DWDM) applications [6]. Afterwards, a Mach-Zehnder modulator, biased at V_π point, is used to create an optical carrier suppressed signal [5]. The mm-wave carrier (f_{mmWave}) is selected at this point by a local oscillator with a frequency equal to half of the desired wireless carrier. As a result, two tones with a spectral difference of f_{mmWave} are generated at the output [5]. The two signals are split and one of them is modulated. Finally, both tones are coupled back and boosted before being distributed through an optical fiber. This scheme is repeated several times to transmit different data streams over different DWDM channels. In the RAU, three functions are performed. First, a wavelength selective switch is used to select the channels to be transmitted. Second, an optical tree beamforming network (OTBN) splits the optical signal into the replicas that will feed the array elements and provides the proper delay configuration. Third, a group of high-bandwidth photodiodes converts the replicas into the mm-wave domain by photonic up-conversion to feed a PAA. This RAU can

Fig. 1. Hybrid mm-wave/optical architecture with beamforming capabilities for next generation of radio access networks. MZM: Mach-Zehnder modulator, AWG: arrayed waveguide grating, VOA: variable optical attenuator, EDFA: erbium-doped fiber amplifier, WSS: wavelength selective switch, OTBN: optical tree beamforming network, PD: photodiode.

wirelessly distribute one or more channels to different antenna stations.

III. INTEGRATED BEAMFORMING NETWORK DESIGN

Beamforming is a key technology which enables wireless communications at mm-wave frequencies. The large signal attenuation at this spectrum region is overcome by using a directive antenna array with steering capabilities. There is a range of options for beamforming techniques [7]. Some desirable features are the integration into microwave photonic systems, broadband operation, small size, lightweight and low loss. This section reports the design of an optical true time delay (OTTD) beamforming network integrated into a PIC. This solution fulfills the above-mentioned requirements and it is compatible with the C-RAN architecture in Fig.1. The photonic integrated chip (PIC) is designed in TriPleXTM technology, which consists of a core layer of SiO₂ sandwiched between two Si₃N₄ stripes [8]. This photonic integration platform is ideally suited for all passive circuits because of the low losses at telecom wavelengths (≤ 0.5 dB/cm) and the high modal birefringence.

Fig. 2 shows the operational principle of an integrated 1x4 OTTD beamforming network for a linear PAA compatible with DWDM optical networks. Although a larger array size is required for practical implementations, the 1x4 configuration, which can also be easily increased, serves as a proof-of-the-concept. Moreover, different chips can be cascaded to provide the desired configuration to different subsections of a larger array. The chip is based on optical ring resonators (ORR) structures acting as delay units. In general, an ORR consists of two waveguides close together. One of them with straight shape and the other one with ring shape. Part of the light propagating through the straight waveguide is coupled to the circular one, and after travelling around the ring, is coupled back to the straight waveguide. As a result, the ring behaves as an optical resonant cavity. The resonance

condition depends on the signal phase after the ring, which can be expressed as $\theta = 2\pi L n_{eff} / \lambda = 2\pi N$, where λ is the wavelength, n_{eff} represents the effective index of the waveguide, L is the length of the ring and N is an integer. At the resonance point, the power transmission is minimized and the group delay is maximized. The separation between resonance points is called free spectral range (FSR) and is given by $FSR = c / (n_{eff} L)$. There are two parameters which can be modified to change the spectral response of the device. First, the amount of light that is coupled to the ring (κ), which determines the group delay. Second, the phase of the signal that is coupled back after the ring (ϕ), which determines the resonance wavelength.

The optical signal launched into the chip consists of one or more non-adjacent 100 GHz DWDM channels. Each channel contains two optical lines, one of them transporting the data modulation, with a spectral difference equal to the desired mm-wave carrier. In the chip, the signal is split into the branches that will feed the array elements according to a symmetric tree configuration (Fig. 2). The paths between the input and the four outputs have the same length and each of them goes through three ORRs with the resonance frequency centered on the optical wavelength which carries the data. Therefore, each output has a minimum delay due to signal propagation and an additional group delay given by the ORRs at the resonance wavelength. Some ORRs are fixed to a minimum group delay (circled in Fig. 2) while the others are used as reconfigurable delay units ($\Delta\tau$). Consequently, a progressive group delay configuration is achieved at the outputs. Afterwards, a high-bandwidth photodiode array converts the optical signal into mm-wave domain [5]. Optical components in non-adjacent DWDM channels are sufficiently separated so that their mixing products are filtered out by the photodiodes bandwidth. The progressive delay given in the optical domain is maintained in the radiofrequency domain [9]. Thereby, several frequency multiplexed channels with the same group delay configuration can be used to feed a PAA.

Fig. 2. Operational principle of a DWDM compatible 1x4 integrated OTTD beamforming network for a linear PAA at mm-wave frequencies.

Fig. 3. Optical ring resonator design and chip layout.

The far-field wave, resulting from the constructive interference of the radiated signals, points to the direction given by:

$$\sin \theta = \frac{c\Delta\tau}{d} = \frac{\lambda\Delta\phi}{2\pi d} = \frac{f_c\Delta\tau}{k}, \quad (1)$$

where θ is the steering angle, $\Delta\tau$ and $\Delta\phi$ represent, respectively, the time and phase difference between consecutive elements, d denotes the distance between adjacent antennas, c is the light velocity in vacuum, λ represents the wavelength, f_c is the mm-wave carrier frequency and k is defined as $k = d/\lambda$. In general, d is fixed to less than the operating wavelength to avoid grating lobes. It can be drawn from Eq. 1 that as the carrier frequency increases, the progressive time delay is shorter. For example, the maximum required progressive delay at 60 GHz is around 20 ps.

Fig. 3 shows the implementation of the ORR in the chip using 2x2 couplers, phase modulators and waveguides. In this structure, the coupling coefficient κ is controlled by a Mach-Zehnder interferometer with a thermo-optic modulator in the upper arm (Modulator A). This phase modulator allows tuning the phase difference between both arms to control the amount of power which is coupled to the ring and, consequently, the group delay that the ORR provides. The switching speed of these modulators and therefore the steering speed is in the order of 0.1 – 1 ms. A second modulator (modulator B) is used in the ring to adjust the resonance wavelength. The pitch between optical modulators and the adjacent waveguides is 250 μm , which corresponds to the minimum distance defined by the foundry design rules. The resonator size defines the FSR and the resonance bandwidth. As the ring becomes smaller, the FSR increases, the maximum achievable delay decreases and the bandwidth increases. Conversely, if the ring length increases, it is possible to achieve a higher group delay at the expense of narrowing the resonance peak. The length is designed to achieve a FSR of 33.3 GHz. There are two reasons for choosing this value. First, it guaranties compatibility with the proposed system architecture. Three delay peaks are situated within every 100 GHz DWDM channel so the same beamforming configuration

can be used for different data streams. Second, it is sufficiently small to provide enough bandwidth and achievable delay to operate at mm-wave frequencies. An additional advantage of reducing the size is the reduction in the power consumption since the modulator resistance is proportional to the length. Fig. 3 also shows the chip layout. The ORRs are connected through couplers and waveguides according to a tree network. Two additional optical outputs are included for monitoring.

IV. SIMULATION RESULTS

The following simulation results validate the operational principle of the PIC and its implementation in the proposed architecture. Fig. 4 shows the group delay at a frequency of 193.33 THz after a single ORR with respect to the voltage applied to phase modulator A. The center frequency was chosen according to the grid presented in Fig. 2 for a mm-wave carrier frequency of 60 GHz. The group delay at the output can be continuously tuned, although it does not show a linear behavior. The minimum delay is 53 ps when 0 V are applied. The maximum delay between consecutive branches which is needed to operate at 60 GHz is around 20 ps. It is possible to achieve that value with a voltage supply of 5.2 V (73 ps).

Fig. 4. Group delay at the output of a single ORR with respect to the bias voltage applied to phase modulator A at a frequency of 193.33 THz.

Modulator B is tuned to fix the resonance of the different ORRs at the same frequency, as it is depicted in Fig. 5. The DWDM grid is also superimposed to show the compatibility with the proposed system. The FSR is 33.3 GHz, so that the distance between delay peaks in the same relative position within a channel is 100 GHz. Therefore, the same beamforming network configuration can be used to transmit different wireless signals received from different DWDM channels. It is also clear that the progressive delay between consecutive outputs is achieved. The insertion loss is around 12.6 dB. However, there is no strict limitation in the input power which can be launched into the chip, so this loss can be compensated by optical amplification. The difference between the resonance point and the maximum is around 1 dB. This is a short variation which can be compensated at the signal modulation stage. There is also a slight variation for each output (<0.5 dB) which adds a small error to the phased

Fig. 5. Group delay and optical gain at the four outputs of the PIC with respect the frequency for an applied voltage of 4.5 V to modulator A.

array, but it is not significant. The other limitation is the delay bandwidth, which decreases as the group delay increases. In Fig. 5, the delay error is kept below 1 ps for 1 GHz bandwidth. This time error is translated into a maximum angular error of few degrees at 60 GHz using Eq.1. This deviation can be overcome with the proper array design. From a system point of view, these results mean that it is possible to transmit several subchannels of 1 GHz at a carrier frequency of 60 GHz, extending the effective bandwidth.

Figure 6 shows the group delay at each output with respect to the bias voltage. The relation is not linear as in the case of a single ORR. Nevertheless, the relative delay between adjacent

Fig. 6. Group delay at the four outputs of the OTBN with respect to the voltage at a frequency of 193.33 THz.

outputs is constant and it can be continuously tuned. This is the main result, since it proves the operation of the OTBN proposed in this work. The group delay of the output 0 is always constant and equal to the minimum group delay that can be provided by the chip, which is 230.7 ps. For 5.5 V, the group delay is 255.4 ps, 280.1 ps and 304.6 ps for outputs 1, 2 and 3 respectively. This configuration assures the proper operation at 60 GHz band with low power consumption. It is also possible the operation at higher frequencies. However, it should be remarked that the photodiode and antenna array design become more challenging.

V. CONCLUSION

The design of a tunable Si_3N_4 mm-wave beamforming chip, fully compatible with a C-RAN architecture, was presented. The periodicity in the spectral response was exploited to use the same configuration for different gigabit frequency-multiplexed channels. This approach allows extending the effective bandwidth of the beamforming network, even though each individual channel is bandwidth limited. A maximum achievable delay of 20 ps enables the beamforming chip to be used at frequencies above 60 GHz, using the proper photodiodes and antenna array. The presented simulation results validate the proposed solution. The chip manufacturing and characterization as well as the system demonstration will be performed in the future.

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