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Wavelength-dependent Continuous Delay based on a Si$_3$N$_4$ Optical Ring Resonator for K-band Radio Beamformer

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Abstract—We present a wavelength-dependent optical true time delay (TTD) for K-band radio beamformer targeting home-satellite communication. A proof-of-concept of optically-assisted radio beamformer with a TTD bandwidth of 2GHz is experimentally demonstrated. The beamformer is capable of generating multiple radio beams if multiple wavelengths are employed.

Keywords—beamformer; coherent; multi-carrier; optical ring resonator (ORR); optical side band filter (OSBF); phase error; wavelength dependent true time delay.

I. 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 tune into a wide range of services such as TV, internet, mobile and other broadband connections provided by different satellites simultaneously. 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-satellite user terminals need to deploy multi-beamforming. Fig. 1(a) shows such a home-satellite system with an optically-controlled radio beamformer. Multiple wavelengths are used to create different delays for feeding antenna arrays. In this way, $N$ radio beams simultaneously point to $N$ satellites or targets. Within a home network, an optical fibre link can be used to provide a wideband seamless connectivity to the devices in each room [4]. An antenna array is mounted in the focal plane of a dish reflector, yielding the so-called focal plane array (FPA). The beamforming in the FPA enables a higher gain and achieves a better performance than a traditional reflector antenna [5].

Several realizations of optically-controlled multi-beam RF beamformers based on discrete components have been reported, however, they are not suited to system integration due to high losses and bulky sizes. Integrated Si$_3$N$_4$ optical ring resonator (ORR) test structures with wavelength-dependent (WD) TTD of 1 GHz bandwidth were realized and characterized for multi-beamforming application as given in [6]. The design implemented a Vernier approach which involves cascading two or more ORRs with different free spectral range (FSRs). This approach, though it meets the requirement of multi-beam optical beamformer, suffers from increased size and tuning complexity due to the use of multiple ORRs.

In this paper, we present an optical integrated circuit generating wavelength dependent delays for the 18-27 GHz range or K-band radio signals. The delays are generated from a single ORR; therefore, a reduced device complexity is achieved. The wavelength tunable delays have a TTD bandwidth of 2 GHz and enable full beam scanning of RF signals in the K-band. By injecting $N$ wavelengths, the WD-TTD can be used to generate $N$ beams simultaneously. A proof-
II. OPERATION PRINCIPLE OF OPTICALLY-ASSISTED RADIO MULTI BEAMFORMER

The diagram in Fig. 2 illustrates a radio multi-beam former 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 representing a building/home local area network. The WD-TTD PIC has $M$ inputs and $M$ outputs, where $M$ is the number of antenna elements. For each antenna element, $N$ wavelengths originating from $N$ lasers are delayed differently. The output of WD-TTD PIC is sent back to a central site where WDM-demux separates the different wavelengths. Then, detected signals of the same wavelength are summed in an $M \times 1$ RF combiner and generate a single beam. In this way, multiple radio beams can be steered simultaneously in the desired directions [$\theta_1, \theta_2, ..., \theta_N$].

III. WAVELENGTH DEPENDANT TRUE TIME DELAY

We have designed and characterized a TTD-PIC based on an ORR targeting RF signals in the K-band. In order to reduce the required bandwidth of the TTD, a single side band modulation is implemented with an optical side band filter (OSBF).

A. Operational Principles

The schematic diagram of the TTD is shown in Fig. 3(a). The OSBF is implemented with Mach-Zehnder interferometric (MZI) structure, in which heaters $A$, $B$, and $C$ are used to provide a tunability of the filter response. The ORR is provided with heater $D$ which is used for thermal tuning of the resonance wavelength and heater $E$ is used for tuning the coupling ratio $\kappa$ of the ORR. The resistance value for heaters $A$, $B$, $C$, $D$ and $E$ are measured to be 575 $\Omega$, 383 $\Omega$, 383 $\Omega$, 575 $\Omega$, and 575 $\Omega$ respectively.

B. Wavelength delay tuning

Fig. 3(b) shows the theoretical plot of the group delay of the realized ORR under different coupling values of $\kappa$. The wavelength delay tuning is done by placing the wavelengths [$\lambda_1, \lambda_2, ..., \lambda_N$] in the ORR delay response as shown in Fig. 3(b). For smaller $\kappa$ values, it is seen that the wavelength vs delay slope is significantly larger. For values of $\kappa$ of 0.5 and larger, the wavelength vs delay slope is significantly smaller, and shows less delay variation in a given wavelength range. The larger the slope, the narrower is the TTD bandwidth. On the other hand, the larger the slope,

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Delay (ps)</th>
<th>rms phase error (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1$ (1552.61)</td>
<td>131.5</td>
<td>1.63</td>
</tr>
<tr>
<td>$\lambda_2$ (1552.62)</td>
<td>132.2</td>
<td>1.62</td>
</tr>
<tr>
<td>$\lambda_3$ (1552.63)</td>
<td>137.4</td>
<td>1.61</td>
</tr>
<tr>
<td>$\lambda_4$ (1552.64)</td>
<td>152</td>
<td>1.5</td>
</tr>
<tr>
<td>$\lambda_5$ (1552.65)</td>
<td>175</td>
<td>1.2</td>
</tr>
<tr>
<td>$\lambda_6$ (1552.66)</td>
<td>199</td>
<td>1.3</td>
</tr>
<tr>
<td>$\lambda_7$ (1552.67)</td>
<td>204</td>
<td>2.4</td>
</tr>
</tbody>
</table>
the larger delay tuning range per unit wavelength is obtained. Therefore, the TTD bandwidth and the resulting delay variation per unit wavelength can be tuned by changing $\lambda$ and thermo-optically varying $\kappa$. Based on this principle, the TTD was characterized while the wavelength input into the TTD was tuned from 1552.61–1552.67 nm. A time delay measurement based on a vector network analyzer (VNA) as described in [7] was used to retrieve phase response measurements. The nearly linear phase measurements results are given in Fig. 4 at the measurement wavelengths ranging from 1552.61 to 1552.67 nm. The solid lines represent the measurement results and the dotted lines represent their best linear fits. The group delay values given in Table. I were derived from the slope of the phase responses, and provide continuous TTD bandwidth of 2 GHz. The delay tuning range from 131.5–204 ps provides full beam-scanning for radio signals in the K-band. The deviation of the phase responses from linearity is quantified in root mean square (rms) error. It can be seen that the rms phase error is less than 2.5° in all cases. The impact of this phase errors on the beamformer gain is minimal.

IV. EXPERIMENTAL SETUP, RESULTS AND DISCUSSIONS

A proof-of-concept of optically-assisted radio beamformer in the frequency range from 18-20 GHz is demonstrated. The experimental setup is given in Fig. 5(a). The fibre-to-chip coupling setup is shown (Fig. 5(a, i)), and DC-probes are used to supply power to the on-chip heating elements. The initial configuration of the heater voltages were set at 12.1 V, 9.4 V, 11.8 V, 8 V and 17.3 V for heaters A, B, C, D and E respectively. The resulting spectrum of the WD-TTD (shown in Fig. 5(a, ii)) provides more than 20 dBs of rejection ratio for double side band to single band conversion.

The experiment consists of two parts. The first part involves testing the functionality of the WD-TTD for continuous bandwidth of 2 GHz. The wavelength of the laser is set at $\lambda_1=1564.15$ nm. An RF stimulus signal from a VNA swept from 18-20 GHz drives a Mach-Zehnder modulator. The output power of the modulator is split into two paths (the reference path designated as $Ch_1$ and the delayed path, designated as $Ch_2$). The SSB modulated signal output of the WD-TTD is shown in Fig. 5(a, iii). The power input into the PDs is variably adjusted with variable optical attenuator (VOA) so that equivalent RF power is obtained after photo detection. Then, the output of the photo-detector is amplified and combined with an RF power combiner. Initially, because the two channels follow two different paths, an inherent phase mismatch happens. To compensate for the length difference between the channels, a fibre optic delay
The second part of the experiment involves data transmission through the combined beamformer channel. An RF signal is generated by up-converting baseband signal to 20 GHz. The base-band signal is a Nyquist-subcarrier multiplexed signal (schematic shown in Fig. 5(d)) with 6 subcarriers ($f_1=120$ MHz to $f_6=970$ MHz) and each of the subcarriers are modulated with a 16-QAM, 120 MBaud data, for a combined rate of 2.8 Gbps. The non-orthogonality in the Nyquist-subcarrier multiplexed signals (as opposed to pure OFDM signals) is suitable for combating carrier synchronization offset in the satellite channels. A square root raised cosine filter with a roll-off factor of 0.2 was employed to band-limit the subcarriers. A guard band of 50 MHz between the subcarriers is included to avoid inter-symbol interference. Then, upon coherent combination, the received signal is down converted to baseband and its spectrum is shown in Fig. 5(d). The measurements on root mean square – error vector magnitude (rms-EVM) of the received signal under coherent combination of the beamformer channels ranged from 10.6 – 12.1 % for subcarrier 1 – 6 as given Fig. 5(e). The corresponding clear constellation diagram is shown in Fig. 5(f). The measurements were done again when there is a delay imbalance i.e. in-coherent combination between the two channels. The resulting rms-EVM values ranged from 29.7 – 38 % for subcarrier 1 – 6 as illustrated in Fig. 5(e). The constellation diagram of subcarrier 1 for in-coherent combination case is shown Fig. 5(g). It can be concluded that quality signal transmission is achieved only via coherent combination of the beamformer channels.

V. CONCLUSIONS

We have presented an on-chip WD-TTD that can be used in a radio multi-beamformer. The measured 2 GHz continuous delay provides enough scanning range for RF signals in the K-band. A proof-of-concept experiment is conducted to validate the TTD bandwidth of the realized chip. A beamforming gain up to 6 dB was achieved indicating coherent combination of the beamformer channels. The variation in the beamformer gain is demonstrated while the delay in a WD-TTD is tuned by changing wavelength of the light source. The resulting decrease in the beamformer gain indicates the shift of the beam in response to the change of delay in WD-TTD. This wavelength dependence of the beamformer gain validates the potential of the WD-TTD to be used for radio multi-beamforming, when multiple wavelengths are used simultaneously. A Nyquist sub-carrier multiplexed signal transmission was successfully conducted through the beamformer. The transmitted multi-carrier signal format is suited to satellite channels supporting multi-user services in which a single subcarrier can be assigned to a single user.

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