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Optical Beamforming Network based on Fiber Optical Delay Lines and Spatial Light Modulators for Large Antenna Arrays

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***Abstract*— An optical beamformer for antenna arrays based on fiber optical delay lines for feeding subarrays and spatial light modulators to change the RF phase of independent antenna elements is proposed. The architecture has the potential to control antenna arrays of a large number of elements. Preliminary experimental results to show the feasibility of the concept are provided.**

***Index Terms*— Microwave photonics, optical beamforming, spatial light modulator.**

I. INTRODUCTION

Optics offers interesting features to the field of antenna array control in comparison with microwave and digital beamforming such low weight, immunity to electromagnetic interference and, especially, true-time delay (i.e. the beam steering angle dependence with frequency, beam squint, is avoided and wide bandwidths can be obtained). There are two main approaches to optical beamforming: true time delay (TTD) systems [1-7], which provide large bandwidths, and phase control systems [7-9], which use a single spatial light modulator (SLM) instead of as many microwave phase shifters as antenna elements.

Since most applications do not require fully TTD control (i.e. the bandwidth of the application is limited), it is possible to combine TTD and phase control to reduce the system cost [8], [10] (providing TTD to subarrays and controlling the relative phase between elements of each subarray). Thus, the beam squint problem is highly reduced for a certain bandwidth whereas the beamforming complexity remains limited.

In this Letter, an optical beamformer for large antenna arrays based on the combination of fiber-optic and free-space components is proposed. Unlike previous proposals [8], the architecture exploits the parallelism of SLMs and free-space optics just for phase generation and implements TTD using fiber optical delay lines (ODL) avoiding collimation and loss issues, and therefore, improving the scalability of the system by reducing the free-space length of the architecture.

II. ARCHITECTURE DESCRIPTION

The architecture is based on providing TTD to subarrays and phase control to the elements of each subarray [10]. As done in previous architectures [8-9], a parallel alignment SLM (PAL-SLM) is used to control the phase of the RF signal of each antenna element. If one polarization component of the light impinging on the PAL-SLM is aligned with the axis of its liquid-crystal molecules, the PAL-SLM can change the refraction index experienced by this signal according to the applied voltage on each pixel. On the other side, light polarized along the orthogonal polarization undergoes a constant refraction index.

Unlike previous proposals based on free-space components to implement time delays [7], we propose the use of fiber optic delay lines to generate TTD. Since present usual applications do not require full TTD control due to their limited bandwidth, the number of subarrays (i.e. TTD units) can be quite limited compared to the number of antenna elements. Thus, parallelism has to be focused on phase control (since independent control is required at each antenna element). Implementing TTD units with bulk components do not exploit the parallelism of free-space optics. On the contrary, TTD implementation requires quite large free-space lengths and that means important problems of collimation and loss. In addition, beam diffraction of many small pixels limits the number of antenna elements to a few since the diffracted beams have to cross through long distances. On the other hand, fiber optic delay lines avoid all these problems, offering low loss and TTD control with a short free-space section (which increases the number of antenna elements that can be controlled with the beamformer).

Figure 1 shows the proposed architecture. A CW laser is amplitude modulated using a dual-drive Mach-Zehnder Modulator (DD-MZM) to generate single sideband (SSB) amplitude modulation. A SLM is used to control the phase of the microwave signal by controlling the relative phase between optical carrier and sideband. Since a correspondence is established between each pixel of the SLM and each antenna element, the phase of a large number of elements can be controlled with a single device. Depending on the applied voltage on each pixel of the SLM, the refraction index in one axis of the SLM can be continuously changed. If the optical carrier is aligned with this axis, the phase of the optical carrier can be controlled. However, if the sideband has an orthogonal polarization, it experiences the constant ordinary refraction index. Thus, the relative phase between signals with orthogonal polarizations can be continuously controlled.

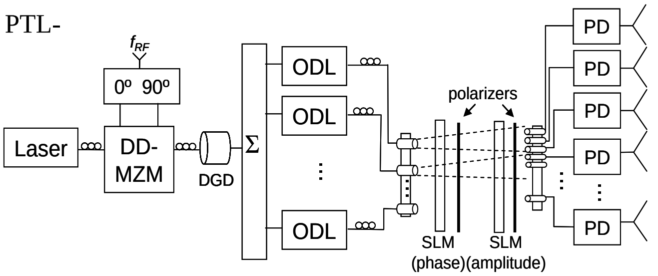

Fig. 1.- Block diagram of an optical beamformer with TTD and phase and amplitude control

Therefore, phase control using SLMs requires the cross-polarization of the optical carrier and its sideband. Previous proposals [8-9] used acousto-optic modulators (AOM) to modulate the CW optical carrier and cross-polarize both signals. However, AOM offer poor bandwidth, frequency range and modulation index compared to conventional external modulators such as MZMs widely available for telecom applications. In addition, AOMs show poor discrimination between optical carrier and sideband polarizations. Due to these limitations, a different approach was employed. Birefringence can be used to cross-polarize two signals with a given wavelength spacing between them, for instance, using a differential group delay module (DGD), which provides group delay between two linear orthogonal polarization states. If an amplitude modulated optical carrier is launched to a DGD and its polarization is linear at 45º with the DGD axis, at the DGD output there is a polarization change with wavelength. Given the phase shift between polarization components caused by DGD ($\varphi=2\pi\cdot f_{RF}\cdot DGD$), to obtain linear orthogonal polarizations between two optical carriers spaced a certain frequency (f_{RF}), the birefringence needed is $DGD=1/(2f_{RF})$.

After the DGD module, the signal is split in as many branches as subarrays the array has. The number of subarrays depends on several factors such as the bandwidth, center frequency, number of elements and spacing between array elements. The time delay provided to each subarray is controlled using fiber optical delay lines (ODL) which can provide large time delays and low loss. After time delaying, the signals are launched to free-space. The output of each line of the beamformer lights a set of SLM pixels (containing, at least, as many as elements in each subarray) and the SLM provides independent phase control to each pixel (i.e. antenna element). After the SLM, a polarizer at 45º is needed to combine the optical carrier and the sideband in a single polarization to allow the generation of a RF signal at the photodiode (PD). The range of phase control of the microwave signal at the antenna elements is the same provided by the SLM if SSB is used (i.e. a SLM with a phase control range of 3π provides microwave phase shifts up to 3π). If dual sideband is used instead of SSB the control of the microwave signal phase is very limited. After the SLM used for phase control, a second modulator and polarizer may be used to control the amplitude of the optical signal of each pixel, allowing the optical tapering of the amplitudes of the antenna array. Then, the signal is collected from free-space and photodetected. Assuming linear orthogonal polarizations for the optical carrier (e.g. y-axis) and the sideband (e.g. x-axis), the microwave signal at the output of the PD can be calculated to be,

$$i_{RF}(t)=E_c^y E_s^x \sin(2\beta)\cos(\omega_{RF}t+\phi_{PAL-SLM}) \qquad (1)$$

where E_c^y and E_s^x are the amplitude of the optical carrier and the sideband, respectively, β is the polarizer angle, and $\phi_{PAL-SLM}$ is the phase shift induced by the SLM on each pixel. The phase of the microwave signal at the photodiode output can be controlled by the relative phase between optical carrier and sideband and the phase shift induced by the SLM is directly translated to the microwave signal.

III. EXPERIMENTAL SETUP

To show the validity of the concept, preliminary experiments have been carried out using the setup of Figure 2.

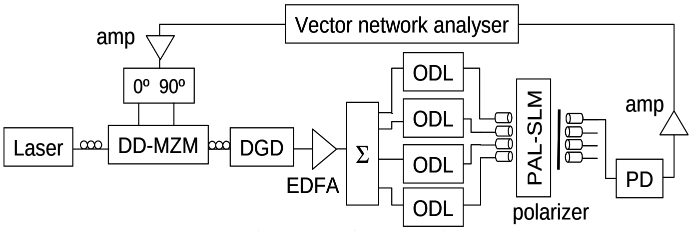

Fig. 2.- Experimental setup of one line of the beamformer

A CW laser (1550 nm, output optical power: 10 dBm) is amplitude modulated using a DD-MZM (its insertion loss, IL, was 9 dB at QB) driven by the output of a vector network analyser (HP8510C). A fixed DGD module (IL=2 dB) is used to cross-polarize the optical carrier and the sideband by means of a differential group delay of around 62 ps. After the EDFA, the signal is split in four channels and each one is time-delayed using an ODL (IL=1.5 dB) and launched to free-space using fiber collimators. A PAL-SLM of 1x128 pixels is used for phase control (IL=3 dB, including collimation loss). After the PAL-SLM, a polarizer is needed to combine in a single polarization state, the polarization states of the optical carrier and the sideband. Finally, a fiber collimator is used to collect the beam and feed the photodiode. The optical insertion loss of the entire beamformer is around 12 dB (taking into account an EDFA gain of 13 dB). The usage of fiber collimators allows the use of high performance pigtailed photodiodes designed for telecom applications.

Figure 3 shows how the phase of an 8 GHz tone can be controlled using the PAL-SLM over a range of 3π. Figure 3 includes the optical characterization of the PAL-SLM to show that the optical shift introduced by the PAL-SLM is translated to the RF tone. A good agreement between the expected and obtained phase shift range is observed.

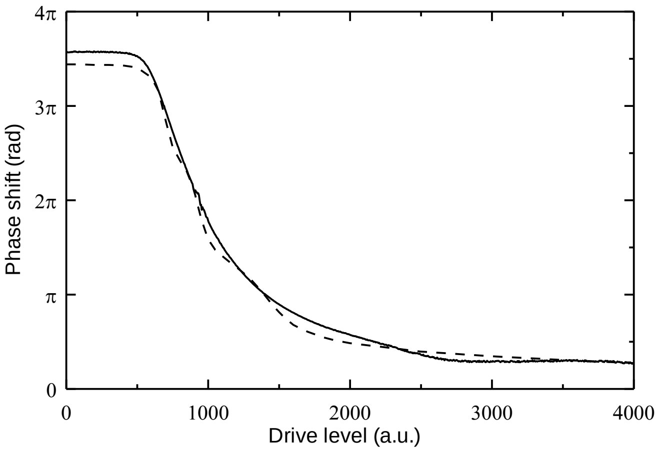

Fig. 3. Phase modulation obtained over an 8 GHz signal (dotted) and optical phase shift obtained from the PAL-SLM all-optical characterization (solid)

In addition to phase control, time delay was also characterized to show the feasibility for providing both phase/time delay control. Figure 4 shows the time delays for each one of the four channels. In the Figure, the relative time delay between the channel corresponding with antenna 1 and the other channels has been shown. Time delays (with four progressive steps: 0, 50, 70, 100 ps) have been measured non-simultaneously using a single photodiode as shown in Fig. 4.

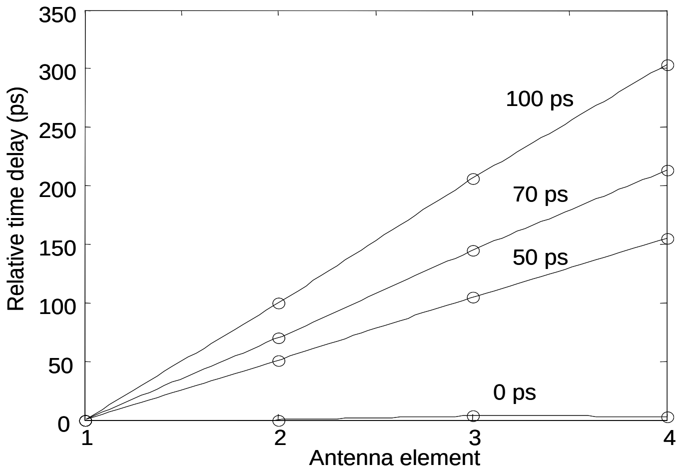

Fig. 4. Time delay measurements obtained for each antenna element and expected progressive time delay between elements. Time delay was measured from the slope of the phase shift with frequency between 6 and 15 GHz using the setup pf Figure 2.

Finally, the architecture has the capability to optically control the amplitude of the microwave signals by adding a second SLM after the PAL-SLM. A TN-SLM was used to show amplitude control, but it limits the performance of the architecture due to the high insertion loss of the particular TN-SLM used in the experiment at 1550 nm (10 dB including the polarizer).

Figure 5 shows the relative amplitude of the microwave signals for different values of the TN-SLM. An amplitude change of more than 20 dB can be obtained.

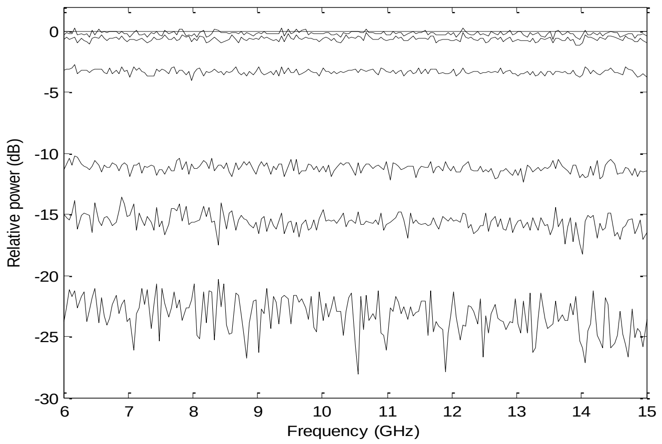

Fig. 5. Amplitude control capability by means of the TN-SLM.

IV. CONCLUSION

An optical beamformer which provides TTD, phase and amplitude control to subarrays and antenna elements, respectively, has been proposed. TTD control is done using fiber ODLs and phase control through free-space PAL-SLM. This combination of free-space and fiber optics optimize the parallelism and the capability to control a large number of radiating elements offering the capability of fully optical control of large antenna arrays.

ACKNOWLEDGMENT

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