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# Highly Scalable Adaptive Photonic Beamformer Using a Single Mode to Multimode Optical Combiner

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***Abstract*—This letter presents a novel architecture for a wideband photonic beamformer. The system is best suited for an adaptive beamforming application related to a highly non-stationary environment, requiring rapid beam steering. Using optical transversal filters for each antenna element, the array is capable of both spatial beamforming and frequency-domain filtering. With the use of a single-mode fiber to multimode fiber coupling technique, our system is highly scalable, and the same set of laser wavelengths can be used for every antenna in the system. Experimental results are presented to show proof-of-concept and demonstrates proposed adaptive beamformer performance.**

***Index Terms*—Adaptive arrays, beam steering, microwave photonics, optical filters, phased arrays.**

## I. Introduction

BEAMFORMERS have attracted considerable interest with wide-ranging applications from radar, communication, microphone, and sensing applications. By controlling the signal amplitudes and delays from each antenna element, the whole array can act in unison to steer the beam pattern [1]. In situations in which there is a highly non-stationary target environment, adaptive beamformers are used to continuously update the beam pattern.

Conventional RF beamformers rely on electrical phase shifters, which limit performance. These suffer from beam squint problems, and beam pointing direction changes with signal frequency, limiting RF systems to narrowband [1]. A wide bandwidth system is necessary for a useful beamformer, and photonics offer broadband operation.

Further, optics offer the advantages of reduced size, weight, power, low transmission loss, and immunity to electromagnetic interference. Electronics cannot practically handle bandwidths in the GHz range, and RF losses can be significant in electronic systems when frequencies are above 100 MHz. RF systems often become bulky and expensive in broad bandwidth systems, as they require downconverters, high speed analog-to-digital (ADC) cards, etc. Light weight and compactness are extremely important in adaptive beamformers that have hundreds of antennas.

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Significant research has been done in the field of wideband beamforming using photonic processing [2]–[5]. True-time delay (TTD) beamformers are popular despite having no ability to filter in the frequency domain. Several methods have been proposed for TTD, focused on delay-and-sum beamforming, using fiber grating prisms [2], fiber-optic delay lines [3], dispersive fiber prisms [4], and cross-gain modulation in SOAs [5]. TTD beamformers are not suitable for adaptive beamformers, since they are either discretely tunable with low resolution or are widely tunable but slow.

Instead of TTD, several beamformers pair a transversal optical filter with each antenna [6], [7]. By changing the weighting of the filters, the beam pattern can be steered in the frequency domain as well. However, neither architecture is scalable to large arrays – the number of lasers required by these systems increases linearly with the number of antennas.

In this letter, we propose a highly scalable adaptive photonic beamformer specifically designed for application in a non-stationary, interfering environment, and we provide preliminary experimental results to show a proof-of-concept demonstration of the architecture. Our beamformer uses optical transversal filters to process the signals spatio-temporally with thermo-optic optical attenuators to adaptively and rapidly adjust the beampattern. Our architecture offers the distinct advantage of scalability to hundreds of antennas, as needed for practical systems, by using a novel single-mode to multimode (SM-MM) combiner. By eliminating coherent effects, our system uses the same fixed set of optical wavelengths for each antenna in the system, resulting in a simple and compact architecture.

## II. System Overview of Photonic Architecture

### *A. Photonic Transversal Filter*

The proposed architecture is shown below in Fig. 1. The backbone of the beamformer is the optical transversal filter. The filter is driven by two eight-channel distributed feedback (DFB) laser arrays. The first array of wavelengths $\lambda_{1-8}$ corresponds to the positive coefficients. The second array of wavelengths $\lambda_{9-16}$ corresponds to the negative coefficients.

The optical sources are inserted into a compact 16-channel thermal-optic attenuator for easy adaptive control of the weights through a computer or voltage source. The attenuators have a response time of 10 $\mu$s per 0.1 dB and a 20 dB range.

The weighted taps are then combined using an arrayed-waveguide multiplexer (AWG Mux). The RF signal to be processed is modulated onto the optical carrier using a dual output electro-optic Mach-Zehnder modulator (MZM). The modulated signals of the outputs are biased at the inverse, $\pi$-shifted, parts of the modulator transfer function. We use this complimentary output

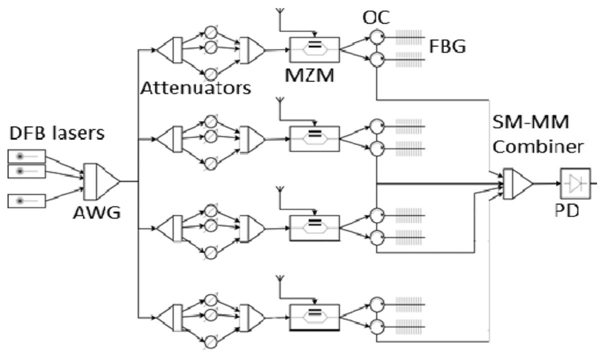


Fig. 1. Architecture for our photonic beamformer. DFB: distributed feedback laser, AWG: arrayed-waveguide grating, MZM: Mach-Zehnder modulator, OC: optical circulator, FBG: fiber-Bragg grating, PD: photodiode.

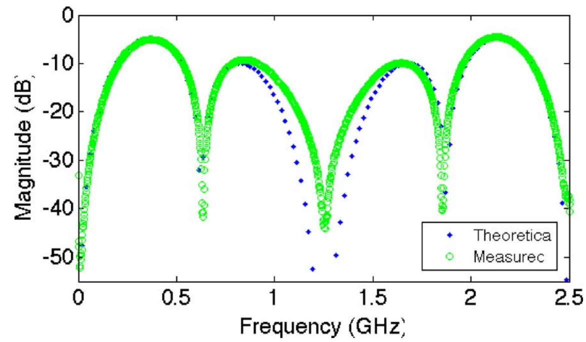


Fig. 2. Measured and predicted magnitude response of eight-tap FIR filter weighted $[1.0914 \quad 1.0617 \quad -1.0715 \quad -1.0814 \quad -1 \quad -0.9683 \quad 0.9795 \quad 0.9594]$.

to implement negative coefficients. Both outputs have equal insertion losses of 3.7 dB.

The weighted signals exit from both the positive and negative outputs of the MZMs. The complementary outputs are launched to fiber Bragg grating (FBG) arrays that only reflect and delay the wavelengths assigned to the respective coefficients, via an optical circulator (OC).

The coefficients encounter FBGs with the same delays, but at different wavelengths. As a result, each delay has both a positive and negative tap, and the attenuators are used to "switch" on the tap and weight each tap by enabling/disabling certain wavelength. In this way, our 16-wavelength filter provides eight positive/negative taps. Since time delays and filter bandwidth are inversely proportional, fabricating FBGs with closer spacing and shorter delays can increase bandwidth.

There is a total optical insertion loss of $\sim 19.5$ dB for each filter. If each DFB laser has 13 dBm of power, each filter receives 9.4 dBm of power after splitting to four antennas and outputs $-10.1$ dBm into the combiner. Assuming a four-antenna beamformer, $-4.6$ dBm of power finally reaches the high speed MM photodetector, well above the $-25$ dBm limit.

### B. Optical Devices for Scalability

The outputs of the optical filters are summed using a special SM-MM optical combiner, as in Fig. 1. The architecture is a blind adaptive approach, in which the adaptive algorithm only has access to the output of the system. This requires a single conversion to RF at the ouput, whereas traditional systems require an ADC for each antenna element, which is impractical for large antenna systems. As a result, conventional criteria such as MMSE cannot be used and analytical Wiener solutions cannot be found. Instead, blind algorithms rely on correlating the processed signal with some known characteristic of the signal of interest (such as frequency), and applying a gradient-based algorithm [8].

Our main advantage is that the same set of 16 wavelengths is used for each antenna, reducing complexity and increasing scalability. Typically, when signals of the same optical wavelength are combined, beat noise from coherent summing will occur and severely degrade the performance. Therefore, without the use of SM-MM combiner the architecture would require 16 lasers for each antenna. To re-use the same wavelengths, the SM-MM combiner is used. The combiner couples signals from several individual single-mode fibers to distinct modes inside a multimode fiber. The combiner offers the advantage of phase-insensitivity and coupling without optical interference. In-depth information and experimental data demonstrating operation can be found in [9].

The architecture scales by simply adding optical splitters and amplifiers up to the limit imposed by the amplified spontaneous emission (ASE) of the amplifiers. The optical weights, which are integrated sixteen per chip and electrically controlled, do not limit the scalability of this architecture, nor does the addition of FBGs. An 100 $\mu$m multimode fiber can accept up to 113 inputs (or antennas).

## *Proof-of-Concept Experimental Results*

### C. Optical Transversal Filter

We experimentally demonstrate an 8-tap filter with tap weights

$$[1.0914 \quad 1.0617 \quad -1.0715 \quad -1.0814 \quad -1 \quad -0.9683 \quad 0.9795 \quad 0.9594]$$

and delays incremented 4 ns. The dark blue dotted curve in Fig. 2 shows the theoretical values and thick light green curve shows the measured magnitude response. We are able to achieve a maximum extinction ratio of $\sim 40$ dB. The bandwidth and the depth and placement of the notches depend on the precision of both the delays and weights. Moreover, our optical system adds no additional noise to the processed signal, as seen in Fig. 2.

The data shows a 4.5 dB loss associated with the architecture. RF systems in the low GHz range exhibit typical losses around 1 dB. RF systems in the high GHz range (60 GHz), an area in which photonic systems are expected to excel, exhibit $\sim 35$ dB loss with one filter and a $\sim 17$ dB loss with a four-filter beamformer [10]. RF signal losses in optical systems in general originate from electrical-to-optical conversion efficiency of the modulators and the modulation depth of the signal during this conversion. To reduce loss further, removal of the optical dc level of the processed signal would allow the signal to be optically amplified further, reducing the system insertion loss (see Fig. 4).

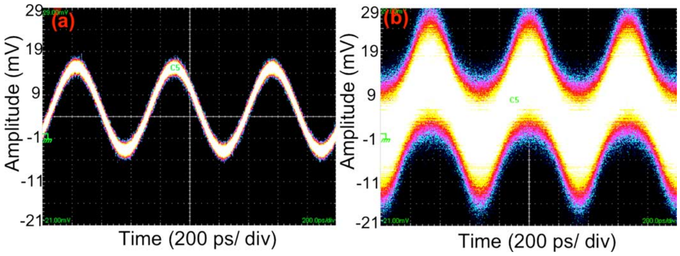


Fig. 3. Signal combination with a. SM-MM combiner b. SM-SM Coupler.

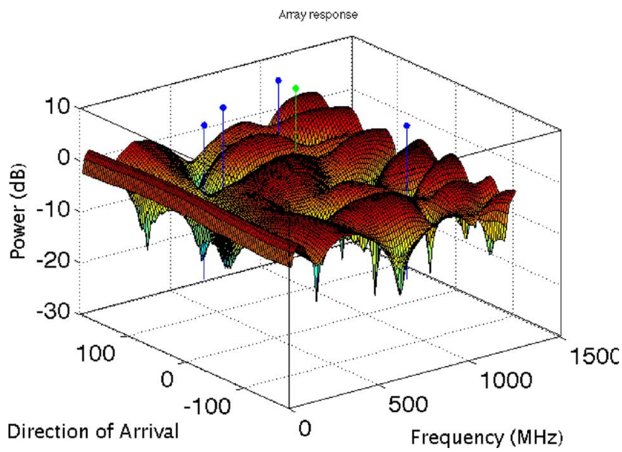


Fig. 4. 3-D wideband beam pattern.

### D. SM-MM Optical Combiner

A CW laser is modulated onto a 1.5 GHz RF sinusoid using an MZM. The modulated signal is split equally with a SM-SM coupler. The two branches are then recombined using the SM-MM combiner in Fig. 3(a) and a traditional SM-SM coupler in Fig. 3(b). Fig. 3(b) shows a severely degraded signal that is extremely noisy. There is no stable signal and the amplitude is everywhere. The signal is much cleaner when the SM-MM combiner is used, demonstrating the prevention of beat noise during signal merging.

### E. Spatio-Temporal Beamforming

Based on the characteristics of our architecture, we simulate the performance of a theoretical circular four-antenna, eight-tap optical beamformer. The beam pattern for a system with SOI of 500 MHz at 90° and interferences at 900, 1000, and 300 MHz at 120°, $-70°$, and 60° respectively demonstrates both the spatial filtering on the $x$-axis and the frequency filtering on the $y$-axis.

### F. Single-Antenna Adaptive Filter

We experimentally demonstrate an adaptive single-antenna beamformer consisting of 8 fully tunable taps with fixed delays of 400 ps and a bandwidth of 2.5 GHz. We employed a modified version of the least means squares (LMS) algorithm shown in [11] called block LMS with a block size of 256 and stepsize of 512. The adaptive results are preliminary. The authors only had access to a single 5 Gs/s ADC card, instead of the two required for the LMS algorithm.

A signal generator fed two narrowband tones at 200 MHz and 1 GHz to the filter. The algorithm was programmed to cancel the 1 GHz interference and pass the 200 MHz signal. Our workaround involved only digitizing the filtered output signal. The input signals were replicated digitally and used to calculate the error signal. The adaptive algorithm then calculates optical weights that are sent to the attenuators. We observed an SIR (signal-to-interference ratio) improvement of $\sim 20$ dB after $\sim 60$ iterations at the output of the filter. We were able to drop the interference to just 5 dB above the noise floor. The results were good and could be easily improved with a second digitizer. In the future, we plan to apply a blind adaptive technique as described previously. Limited resolution associated with the optical attenuators degraded performance.

## III. Conclusion

A photonic adaptive beamformer has been proposed. Optical transversal filters are used for spatio-temporal beamforming. Experiments demonstrate proof-of-concept adaptive filtering. Close agreement between predicted and measured magnitude response was observed. Adaptive experiments were run.

The beamformer has been designed for an application of a dynamic interfering environment. The SM-MM combiner enables the architecture to be highly scalable. Future work will include the construction of multiple transversal filters to complete true spatial beamforming capability.

## References

[1] J. Yao, “A tutorial on microwave photonics,” *IEEE Photon. Soc. News*, vol. 26, no. 3, pp. 5–11, Jun. 2012.

[2] H. Zmuda, R. A. Soref, P. Payson, and S. Johns, “Photonic beamformer for phased array antennas using a fiber grating prism,” *IEEE Photon. Technol. Lett.*, vol. 9, no. 2, pp. 241–243, Feb. 1997.

[3] L. Jofre, C. Stoltidou, S. Blanch, T. Mengual, B. Vidal, J. Marti, I. McKenzie, and J. M. del Cura, “Optically beamformed wideband array performance,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 6, pp. 1594–1604, Jun. 2008.

[4] M. Y. Frankel, P. J. Matthews, and R. D. Esman, “Two-dimensional fiber-optic control of a true time-steered array transmitter,” *IEEE Trans. Microw. Theory Tech.*, vol. 44, no. 12, pp. 2696–2702, Dec. 1996.

[5] X. Weiqi and J. Mork, “Microwave photonic true time delay based on cross gain modulation in semiconductor optical amplifiers,” in *Proc. OptoeElectron. Commun. Conf. (OECC)*, 2010, pp. 202–203.

[6] H. Zmuda and E. N. Toughlian, “Broadband nulling for conformal phased array antennas using photonic processing,” in *Proc. Int. Topical Meeting Microw. Photon. (MWP)*, 2000, pp. 17–19.

[7] N. A. Riza, “High speed multi-beamfoming for wideband phased arrays,” in *Proc. Int. Topical Meeting Microw. Photon. (MWP)*, 2003, pp. 405–409.

[8] T. Ohira, “Analog smart antennas: An overview,” in *Proc. PIMRC*, 2002, pp. 1502–1506.

[9] M. P. Fok, Y. Deng, K. Kravtsov, and P. R. Prucnal, “Signal beating elimination using single-mode fiber to multimode fiber coupling,” *Optics Lett.*, vol. 36, no. 23, pp. 4578–4580, Nov. 2011.

[10] S. Lin, K. B. Ng, K. M. Luk, S. S. Wong, and A. Poon, “A 60 GHz digitally controlled RF beamforming array in 65 nm CMOS with off-chip antennas,” in *Proc. Radio Freq. Integr. Circuits Symp. (RFIC)*, 2011, pp. 1–4.

[11] B. Widrow, P. E. Mantey, L. J. Griffiths, and B. B. Goode, “Adaptive antenna systems,” *Proc. IEEE*, vol. 55, no. 12, pp. 2143–2159, Dec. 1967.