

Wideband Multi-Beamforming Using Programmable Microwave Photonic Signal Processing Units

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Abstract—In this project, wideband RF beamforming technologies based on optically controlled true time delays are investigated. Firstly, a generalized pattern multiplication method with frequency-dependent array factor is proposed to evaluate the performance of a wideband beamforming network. Then, two kinds of programmable microwave photonic signal processing units are proposed. One is a compact structure which is specially designed for 2-D beam steering. The other consists of multiple highly reconfigurable microwave photonic filters which can be used for general purpose and multi-beamforming.

Index Terms—optical beamforming, microwave photonic filter, and true time delay

I. INTRODUCTION

WIDEBAND beamforming plays an important role in systems such as ultra-wideband communication, radar imaging and electronic warfare, in which true time delay (TTD) is essential to overcome the beam-squint problem induced by the system based on phase shifters. Thanks to the advantages in terms of large bandwidth, low loss and immunity to electromagnetic interference brought by photonic technologies, delaying microwave signals in the optical domain become extremely attractive. As the fast development of modern radar and communication systems, there is increasing demand for multi-task phased-array antennas where independent beam-steering of multiple RF signals with different frequencies is required. This project tries to go beyond the state of the art, in which two kinds of novel programmable microwave photonic signal processing units for wideband multi-beamforming are proposed. In addition, the concept of the array factor in narrow band phased-array antenna is adapted to the wideband scenario, in which a generalized pattern multiplication method with frequency-dependent array factor is investigated.

II. FREQUENCY-DEPENDENT ARRAY FACTOR

For a conventional phased-array antenna system with identical elements, the radiation pattern of the array can be calculated by the pattern multiplication method, in which the total far-field is equal to the field of a single element multiplied

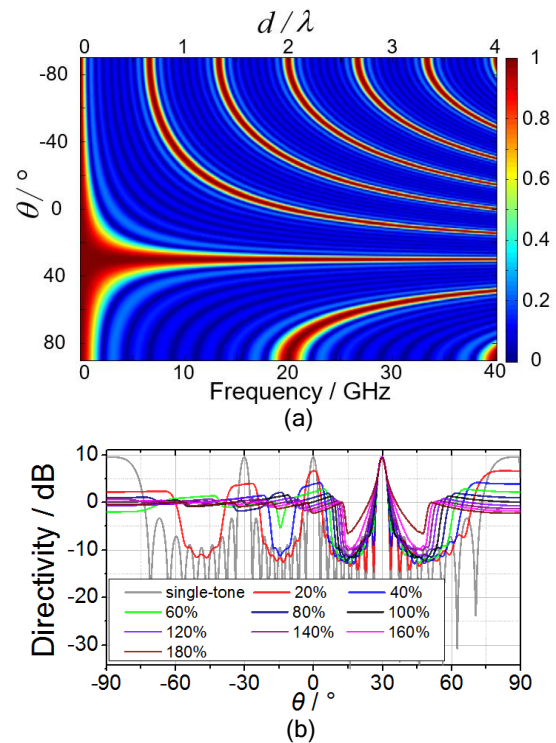


Fig. 1. (a) The magnitude of the normalized frequency-dependent array factor for a 9-element, 3-cm spacing wideband array with the main lobe oriented to 30° and (b) energy pattern of a TTD array transmitting LFM signals with a 10-GHz center frequency and different fractional bandwidths.

by the array factor. However, the array factor for a phase shifter-based array does not take the signal frequency into account. In this project, a generalized pattern multiplication method to describe the synthesized radiation pattern of a TTD based wideband antenna array is proposed [1]. The key term in the pattern multiplication method is the frequency-dependent array factor which can be derived from the frequency responses of programmable microwave photonic signal processing units and the geometrical arrangement of the antenna elements. Based on the array factor, wideband far-field patterns of a wideband array can then be achieved taking into account the radiation pattern of the antenna element and the spectrum of the feeding signal. The frequency-dependent array factor of a one-dimensional uniform linear array with ideal TTDs is analyzed and numerically studied as shown in Fig. 1(a). Results show that a TTD-based beamformer together with a wideband linear frequency-modulated (LFM) feeding signal can effectively suppress the grating lobes, as depicted in Fig. 1(b).

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III. 2-D BEAMFORMING WITH COMPACT MICROWAVE PHOTONIC SIGNAL PROCESSING UNITS

A simple way to realize simultaneous steering of multiple RF beams is to repeat the optical TTD network for single beam since the immunity to electromagnetic interference brought by photonic technologies would significantly suppress the crosstalk between the signals for multiple beams. Thus, a compact beamformer for single beam steering is highly desired to achieve an optimized multi-beamforming system, especially for a planar antenna array where time delays of signals are required to be controlled in two independent dimensions. In this project, a hardware-compressive optical true time delay architecture for 2-D beam-steering is proposed based on a set of compact microwave photonic signal processing units [2], as shown in Fig. 2(a). Utilizing a tunable dispersive element as the

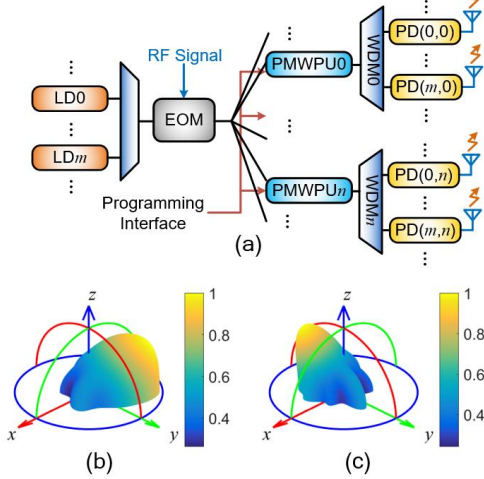


Fig. 2. (a) Schematic diagram of the proposed optical 2-D TTD beamformer and the calculated energy patterns with main lobes oriented to (b) $(\theta, \varphi) = (45^\circ, 135^\circ)$ and (c) $(\theta, \varphi) = (30^\circ, -60^\circ)$. LD: laser diode; EOM: electro-optic modulator; PMWPU: programmable microwave photonic signal processing unit; WDM: wavelength-division multiplexer or demultiplexer; PD: photodetector.

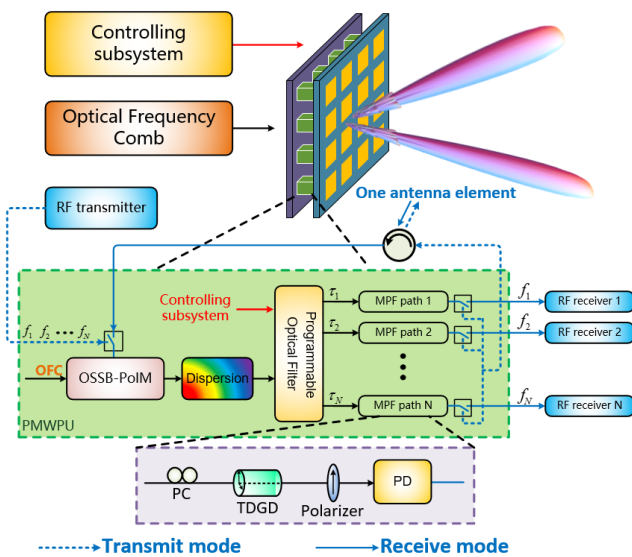


Fig. 3. Schematic diagram of the wideband multi-beamforming system using programmable microwave photonic signal processing units with highly reconfigurable microwave photonic filters. OSSB-PoIM: optical single sideband polarization modulation module; MPF: microwave photonic filter; PC: polarization controller; TDGD: tunable differential group delay line.

key component, the programmable unit can simultaneously control time delays on multiple paths, in which the step time delay between two adjacent paths and the common delay for all the paths can be programmed independently. Therefore, for an $M \times N$ planar antenna array, only one stage of N units and M wavelength-fixed optical carriers are needed to steer a single beam in both azimuth and elevation directions. An experiment is carried out to demonstrate the delay controlling in a 2×2 array which is fed by a wideband pulsed signal. Energy patterns calculated from the experimentally measured waveforms are illustrated in Fig. 2(b) and 2(c).

IV. PROGRAMMABLE MICROWAVE PHOTONIC SIGNAL PROCESSING UNIT BASED ON HIGHLY RECONFIGURABLE MICROWAVE PHOTONIC FILTERS

The concept of T/R module in an active electronically scanned array can be applied to the optical TTD network, where each antenna element in the array would have its own “optical T/R module”, i.e., the programmable microwave photonic signal processing unit, for independent and simultaneous time delay controlling of multiple RF signals, as illustrated in Fig. 3. Thus, the reconfigurability of the optical wideband beamformer could be notably enhanced, in which the RF spectrum resource and antennas could be flexibly assigned to multiple tasks. In this project, a new structure of the programmable unit is proposed based on our previous work in [3]. Microwave photonic filters in the programmable unit are significantly improved, in which optical single sideband polarization modulation [4] and multiple optical carriers in an optical frequency combs [5] are introduced to realize the tunability in both the center frequency and the band-pass width.

V. CONCLUSION

In this project, two kinds of programmable microwave photonic signal processing units are proposed for wideband multi-beamforming. The array factor and the pattern multiplication method are adapted to the wideband scenario. The results could find potential applications in multi-task radar, satellite communication and other wideband RF systems.

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