Transmit/Receive Module of Multiwavelength Optically Controlled Phased-Array Antennas

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***Abstract*— We report on a transmit/receive module of multiwavelength optically controlled phased-array antennas. Both transmit and receive mode of the module employs a single programmable dispersion matrix to provide true time delays for all antenna elements. The multiwavelength receiver combines antenna signals in the optical domain without suffering from coherent interference. Therefore, squint-free receiver over a broad frequency band can be achieved. Experimentally, squint-free beam receiving with 2-b scan angle resolution is demonstrated over an equipment-limited frequency range from dc to 4 GHz.**

***Index Terms*— Phased arrays, gratings, wavelength-division-multiplexing, optical delay lines.**

OPTICALLY controlled phased-array antennas (OCPAA) with true time delay are of interest. The use of optics to control PAA's compares favorably with conventional electronics in terms of loss, weight, size, bandwidth, and susceptibility to electromagnetic interference. Most importantly, OCPAA with true time delay features squint-free beam steering and a large instantaneous bandwidth. Wide-band beam steering for the transmit mode of OCPAA has been successfully demonstrated by many proposed optical beamforming networks [1]–[10]. However, in order to exploit the advantages of OCPAA, the optical beamforming network must be functional in both transmit and receive mode. Earlier works in OCPAA receivers employed a microwave mixer at each element, which resulted in a narrow bandwidth [7]. Recently, it has been shown that large bandwidth can be achieved in the receive mode by optically combining the received signal [8]. However, the optical combining in [8] is performed with a split, tunable single-wavelength laser source and is subject to optical coherent noise.

The optical coherent noise can be avoided by employing multiple optical carriers with distinctive wavelengths [2], [3], [6], [9], [10]. For example, we have reported a multiwavelength optically controlled phased array antenna (MWOCPAA) transmitter that employs a multiwavelength laser source and a programmable dispersion matrix (PDM) [9], [10]. In this letter, we further exploit the multiwavelength concept to develop a MWOCPAA transmit/receive (T/R) module. This multiwavelength scheme offers advantages over other wavelength-division-multiplexed (WDM) approaches adopting a single tunable laser because: 1) it completely eliminates the coherent beating noise; 2) the optical wavelength demultiplexing/multiplexing avoids optical splitting/combining loss; and 3) it offers common beam forming network for both T/R modes.

Fig. 1(a) shows the schematic diagram of the MWOCPAA T/R module. The module employs distinctive wavelength for each array element, and a multiwavelength laser source for the entire array. The transmit and the receive mode share a single PDM. The 2×2 optical switches are placed at the array elements, before the electrooptic modulator (EOM), and after the PDM serve to switch between the transmit and the receive mode. The BAR state (or "through" state) and the CROSS sate of the switches correspond to the transmit and the receive mode, respectively. The transmit mode has been reported in [9], [10]. In the receive mode, unmodulated optical wavelengths are routed directly to a remote antenna. A WDM multiplexer directs each optical wavelength to an array element, establishing a one-to-one correspondence between the optical wavelengths and the array elements. Each array element is equipped with an EOM to modulate the received microwave signal onto the optical carrier. The modulated optical carriers are then remultiplexed through the same WDM multiplexer into one single fiber and sent to the PDM for true time delay processing. The details of PDM has been reported previously [10]. The PDM is a wavelength-dependent time delay unit consisting of 2×2 optical switches and dispersive elements such as dispersive fibers and Bragg fiber gratings. By programming the optical switches, the PDM generates a time shift across the optical wavelengths. The PDM-processed optical carriers are then combined on a single photodetector. The spacing between adjacent optical wavelengths can be arranged (e.g., 1 nm or 120 GHz) such that frequencies of optical beating signals among different wavelengths are beyond the bandwidth of the photodetector. The received beam angle is determined when the photocurrent is maximized, or in other words, when the PDM offsets the time delays among the optical carriers.

To demonstrate the concept of the MWOCPAA receiver, we have constructed a prototype with two elements and a 2-b scanning resolution. Two external-cavity tunable semiconductor lasers are employed to provide optical wavelength carriers at 1546.88 and 1547.53 nm. Potentially, monolithic multiwavelength sources developed for telecommunication applications can be used to provide all the optical wavelengths in MWOCPAA [11]. Two EOM's are used to modulate the received microwave signal onto the optical carriers. The incoming signals are simulated by splitting the output of an

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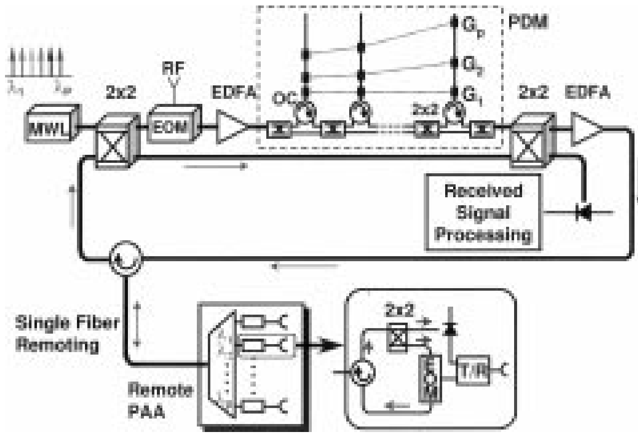

Fig. 1. Schematic diagram of the MWOCPAA T/R module. The T/R operation are controlled by the 2×2 optical switches outside the PDM. OC: Optical circulator, 2×2: 2×2 optical switch. G_i: Grating matched to λ_i.

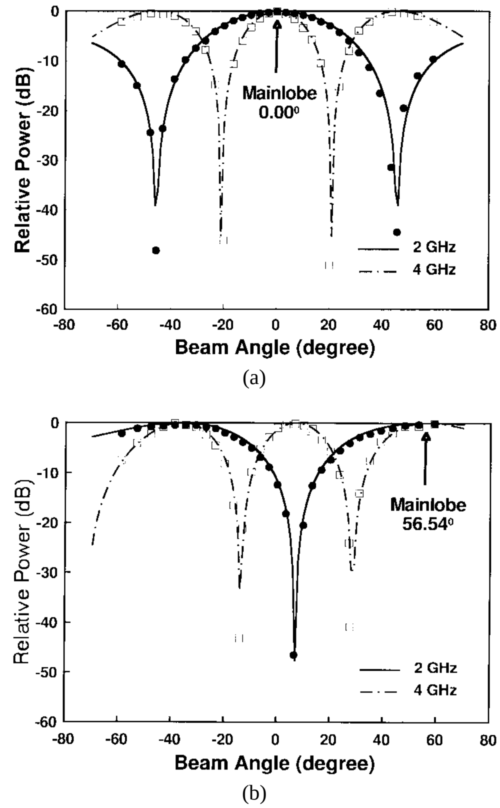

Fig. 2. Measured and calculated beam pattern at 2 and 4 GHz. The mainlobe is located at: (a) broadside when the modulated optical wavelengths "skip" the fiber gratings in both stages of the 2-b PDM; (b) 56.54° when the modulated optical wavelengths are routed through the fiber grating in both stages of the 2-b PDM.

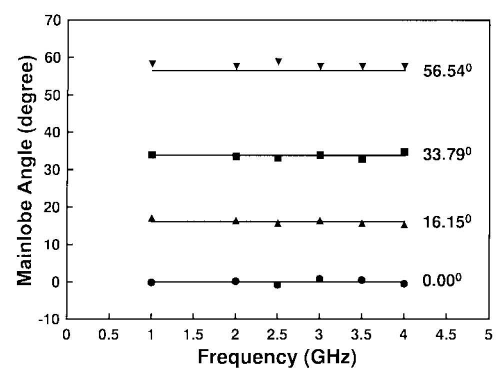

Fig. 3. Mainlobe locations versus microwave frequency for various PDM settings. Squint-free beam receiving is measured across an instrument-limited frequency span from dc to 4 GHz.

HP microwave synthesizer and individually delaying the split signals using microwave phase shifters. The modulated optical carriers are multiplexed and sent to the 2-b fiber grating PDM for true time delay processing. Two gratings are implemented in each stage of the PDM to reflect the corresponding optical wavelengths. The grating spacings in the first and the second stages of the PDM are 1 and 2 cm, respectively. All gratings have a reflectivity of 85% and a FWHM bandwidth of 0.15 nm. The output of the PDM is fed into a high-speed photodetector. The detected microwave signal is amplified by a low-noise amplifier and is displayed on a microwave spectrum analyzer.

Assuming an array element spacing of 10.5 cm (0.7λ at 2 GHz), the corresponding beam angle is obtained by adjusting the relative phases of the two microwave signals feeding the EOM's. Fig. 2 shows the measured and the calculated received beam patterns at 2 and 4 GHz. In Fig. 2(a), the optical switches in the PDM are configured such that the optical wavelengths do not pass through gratings in either stage. The mainlobe is thus located at broadside. When the optical switches are programmed to route the optical wavelengths through the gratings in both stages, the mainlobe is steered to 56.54°, as shown in Fig. 2(b). Since only two array elements are assembled here, the received beam patterns in Fig. 2 contain grating lobes of equal amplitude as the mainlobe and broad beamwidth is observed. The beam pattern can be improved by tailoring the spacings among the array elements to suppress the grating lobe across a wide frequency range [7], [8], and by increasing the number of array elements to reduce the beamwidth. Next, squint-free beam receiving is demonstrated in Fig. 3. Here, the PDM is programmed to steer the mainlobe at 0.00°, 16.15°, 33.79°, and 56.54°, respectively. The measured beam angles are independent of the microwave frequency and show good agreement with the predicted values. The deviation is less than $\pm 3°$ and is attributed to random phase shifts in microwave cables, amplifiers, and error in grating spacing.

It should be emphasized that the bandwidths of the microwave phase shifters used in this experiment limits the maximum measurable frequency to 4 GHz. The microwave phase shifters, which are employed in our demonstration to simulate the beam angle of the received signal, are not part of the MWOCPAA T/R module, and are not required for actual implementation. The true optical combining in MWOCPAA T/R module exploits the large instantaneous bandwidth offered by true time delay. The number of fiber gratings required in this scheme is linearly proportional to the bit-resolution of the beam angle [9], [10]. Compared with other WDM schemes [3]–[6], in which the number of fiber gratings increase somewhat exponentially with the bit-resolution, the MWOCPAA T/R module is hardware-compressive. Moreover, since each optical wavelength is routed to an assigned array element by the WDM multiplexer, the multiple wavelengths system is therefore free of optical splitting loss. This makes the MWOCPAA T/R module particularly attractive for large phased-array systems.

The optical insertion loss in the MWOCPAA T/R module is a potential concern. Each PDM stage includes insertion loss contributed from the optical switch (α_s), fiber grating (α_g), and the optical circulator (α_c). Based on typical loss values ($\alpha_s = 1$ dB, $\alpha_g = 0.5$ dB, $\alpha_c = 1$ dB), an n-bit PDM has an insertion loss of $(3.5 \cdot n + 1)$. In addition, optical insertion loss through the transmit and the receive paths are estimated to be −13 and −28 dB, respectively. The insertion loss of the PDM and the optical path is independent of the array size and can be compensated by using optical amplifiers. Erbium-doped fiber amplifier (EDFA) with 30 dB gain, 30-dBm saturation output power, and 7-dB noise figure is commercially available [12]. As an example, we illustrate the implementation of these EDFA's in a 10-b MWOCPAA T/R module with 16 wavelengths. The EDFA's are placed before and after the PDM, as shown in Fig. 1. The insertion loss of the 10-b PDM is −36 dB. Following the optical path in Fig. 1, an output power of −10-dBm/wavelength from the multiwavelength laser source results in a received optical power of −2 dBm for each array element in the transmit mode, and a total received optical power of −7 dBm in the receive mode. Similarly received optical powers are achievable using EDFA's with lower saturation output power. This is accomplished by adjusting the EDFA's arrangement; for instance, an additional EDFA can be inserted within the PDM. The corresponding RF link efficiency in the transmit and the receive mode are calculated to be −35 and −45 dB, respectively. The RF link efficiency can be improved by including microwave amplifiers in the module. The spontaneous emission noise from the EDFA's induce a higher effective laser relative intensity noise (RIN) which affect the noise figure of the link [13]. Our calculation shows that the effective laser RIN for each optical wavelength are −123 (transmit) and −136 dB/Hz (receive), respectively. These figures are dominated by the spontaneous emission noise of the EDFA's. In the receive mode, the incoherent summation of RIN-induced noise currents from various optical wavelengths further reduces the overall laser RIN by a factor of m, where m is the number of optical wavelengths [14].

It should also be noted that the insertion of the PDM is path-dependent. The path dependent insertion loss in the PDM can be corrected by replacing the fiber in the lower path at each PDM stage with: 1) optical attenuator to equalize the insertion loss or (2) fiber fabricated with gratings in reverse sequential order with respect to the that in the upper path to construct a "two-side" fiber grating PDM.

In conclusion, we have developed a multiwavelength optically controlled phased-array transmitter/receiver module. The module adopts multiple optical wavelengths and a programmable dispersion matrix to simultaneously generate all the necessary time delays for beam forming. This multiwavelength scheme realizes beam receiving over a broad frequency range by combining antenna signals in the optical domain without suffering from coherent interference. The receive mode of the module is demonstrated with a 2-b experimentally prototype. Squint-free beam receiving is observed over a frequency range from dc to 4 GHz, which is only limited by the bandwidth of our equipment.

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