A Novel Multiwavelength Optically Controlled Phased Array Antenna with a Programmable Dispersion Matrix

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Abstract— **We propose and demonstrate a "programmable-dispersion" matrix (PDM) for a novel multiwavelength optically controlled phased array antenna (MWOCPAA). The PDM, when employed in conjunction with a multiwavelength source, generates all the time delays for the entire array. In this multiwavelength control scheme, an optical wavelength-to-array element correspondence is established and there is no splitting loss associated with signal distribution to array elements. The time delays are controlled by the dispersion of the PDM which can be programmed by optical switches. Experimental results demonstrating the feasibility of the MWOCPAA are presented. Broadband linear RF phase shift is measured among various wavelength channels.**

OPTICS OFFERS many advantages in true time delay phased array antenna system such as wide instantaneous bandwidth and squint-free beam forming. Although many optically controlled phased array antennas (OCPAA) architectures have been realized [1]–[8], the overall system cost, complexity and robustness criteria must be met before the system can be practically deployed. Recently, there has been a great deal of interest to use the wavelength dimension of lightwaves to simplify the architecture [4]–[8]. Most of these approaches use a single tunable wavelength to control the scanning angle, and does not fully exploit the parallelism of photons in the wavelength domain. In this letter, we propose and demonstrate a novel multiwavelength-OCPAA (MWOCPAA) with true time delay that employs a "programmable-dispersion" matrix (PDM) in conjunction with a multiwavelength laser source. In this multiwavelength control scheme, a one-to-one correspondence is established between the array elements and the optical wavelength channels. True-time delay to the element is achieved by using only one PDM for the entire array. In addition to hardware compressiveness, another unique advantage of MWOCPAA is that there is no optical or RF splitting loss associated with the signal distribution.

The proposed MWOCPAA is shown in Fig. 1. It consists of a monolithic mode-locked laser which functions as the multiwavelength source, an external electro-optic (EO) modulator, a PDM and a wavelength-division-multiplexed (WDM) demultiplexer. The PDM with n-bit resolution comprises n "dispersive" elements with exponentially increasing dispersion, $D_o, 2 \cdot D_o, \cdots, 2^{n-1} \cdot D_o$ (ps/nm), and $(n+1)$ 2×2 optical switches to program the total dispersion, as illustrated in the inset of Fig. 1. The dispersive elements can be made of any wavelength-dependent time-delay units such as dispersive fibers, grating fibers, or WDM delay lines. The total dispersion of the PDM is then

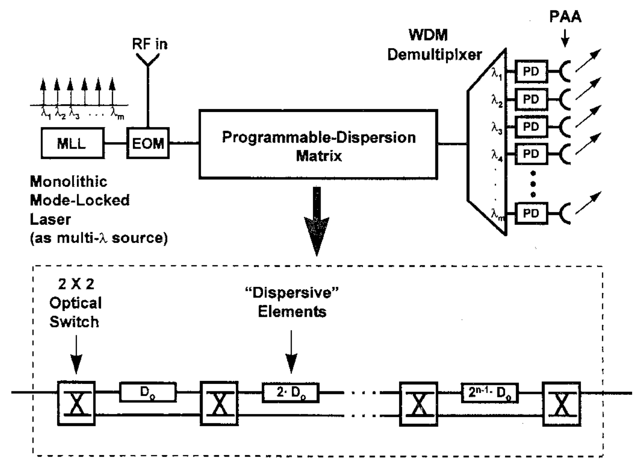

Fig. 1. Schematic diagram of the proposed MWOCPAA architecture using a multiwavelength laser and a programmable dispersion matrix.

$$D_{\text{TOT}} = \sum_{i=1}^{n} 2^{i-1} \cdot D_o \cdot S_i \tag{1}$$

where $S_i = 0$ or 1 is the state of the ith optical switch. By programming the optical switches, the total dispersion of the PDM can vary from 0 to $(2^n - 1) \cdot D_o$ ps/nm in increments of D_o ps/nm. In contrast to the conventional switched-delay lines [9], the PDM creates wavelength-dependent reltive time delays among various wavelength channels.

The monolithic mode-locked laser provides a mode-locked "supermode" that consists of m equally-spaced wavelength $\lambda_1, \lambda_2, \cdots, \lambda_m$. To demonstrate the effectiveness of monolithic mode-locked laser as multiwavelength laser source, a double-grating demultiplexer has been employed to extract six uniformly spaced wavelength channels ($\Delta\lambda = 0.33$ nm) from a 39.5 GHz monolithic colliding-pulse mode-locked (CPM) semiconductor laser [8], as shown in Fig. 2(a). The side-mode-

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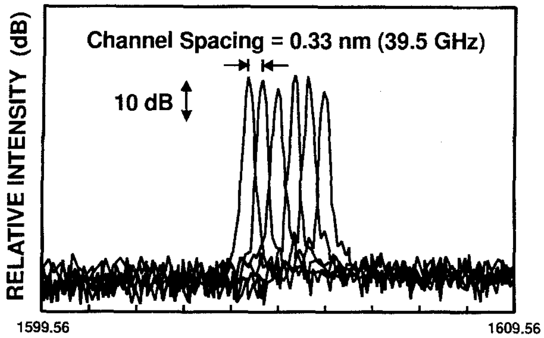
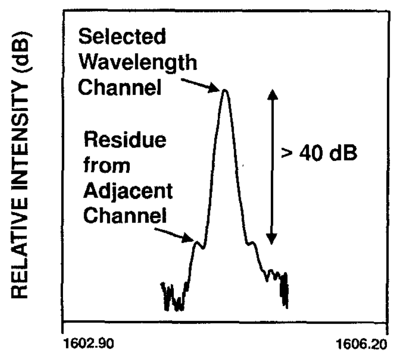


(a)



(b)

Fig. 2. (a) Six wavelength channels extracted from a 39.5 GHz monolithic mode-locked semiconductor laser by using a double-grating demultiplexer. (b) Side-mode-suppression-ratio for each wavelength channel is greater than 40 dB.

suppression-ratio of each wavelength channel is greater than 40 dB [Fig. 2(b)].

The multiple wavelengths are simultaneously modulated by the external EO modulator and then sent through the PDM for true-time delay processing. The resulting time delay between adjacent optical channels is

$$\Delta T = D_{\text{TOT}} \cdot \Delta\lambda \tag{2}$$

where $\Delta\lambda$ is the channel spacing. If the PDM is implemented using dispersive fibers, uniform wavelength spacing is required. This is achieved by using the mode-locked supermode as the multiwavelength source in which the wavelength spacing is precisely equal to the mode-locking frequency. The WDM demultiplexer directs λ_i to the ith element of the array, generating a relative linear time shifts of $\{0, \Delta T, 2\Delta T, \cdots, (m-1)\cdot \Delta T\}$ across the array elements. The steering angle θ is

$$\theta = \sin^{-1}(c \cdot \Delta T/\Lambda) \tag{3}$$

for all RF frequencies, where Λ is the distance between array elements, and c is the velocity of light in free-space.

To demonstrate the feasibility of this architecture, an experimental prototype MWOCPAA with 2-bit resolution as shown in Fig. 3 is constructed. In this initial demonstration, a 2.3-km

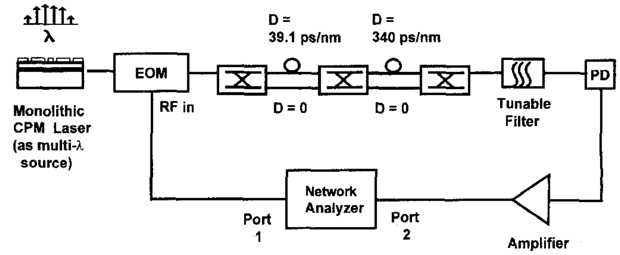


Fig. 3. Experimental setup for characterizing the relative RF phases of the MWOCPAA with a 2-bit PDM.

and a 20-km long fiber lines with 17 ps/km-nm are employed in the PDM, which gives rise to effective dispersions of 39.1 ps/nm and 340 ps/nm, respectively. An 80 GHz monolithic CPM InGaAs–InGaAsP quantum well laser is used as the multiwavelength source [10]. The CPM laser is passively mode-locked at 1546.41 nm with a mode spacing of 0.60 nm. The reduced mode partition noise in the mode-locked laser makes it a suitable multiwavelength source for our application [11]. The RF signal is applied to all wavelengths through an external EO modulator with 5 GHz bandwidth. A tunable fiber Fabry–Perot filter with 10 GHz bandwidth is placed after the PDM to select different wavelength channels for RF phasing measurement. The selected channel is fed to a high-speed photodetector. The RF phase is measured by the HP 8510 RF network analyzer.

Fig. 4(a) and (b) shows the measured relative RF phase shifts for total dispersions of 39.1 ps/nm and 340 ps/nm, respectively, as a function of the RF frequency for various wavelength channels. Very linear phase shift with frequency is observed for the entire bandwidth of the modulator, as predicted by the theoretical calculation. Relative time delays of 23.5 ps and 204 ps are obtained between adjacent channels for these two dispersions, respectively. This agrees very well with the theoretical calculations. A more compact PDM can be realized by replacing dispersive fibers with grating fibers as "taylorable-dispersion" fiber, which has the added advantage of eliminating the signal dispersion.

There is no optical and RF sp;itting loss associated with signal distribution in MWOCPAA. Since each antenna element is assigned a distinctive wavelength channel by the WDM demultiplexer, the optical splitting loss is eliminated. Moreover, the simultaneous modulation of all the optical channels by a single EO modulator removes the RF splitting loss. The optical insertion loss of the PDM is estimated in the following. Since the n-bit PDM requires $(n+1)$ 2×2 optical switches and the typical optical insertion loss of an optomechanical switch is 1 dB, the overall optical insertion loss of a n-bit PDM is $(n+1)$ dB. Typical optical insertion loss of commercially available WDM demultiplexer is about 3 dB, independent of the number of the optical channels. Therefore, the total optical insertion loss from the input of the PDM to the output of the WDM demultiplexer is $n+$ 4 dB, independent of the number of array elements. This insertion loss can be compensated by optical or RF amplifiers.

The array size can be scaled up by increasing the number of optical channels or by wavelength re-use. Multiwavelength

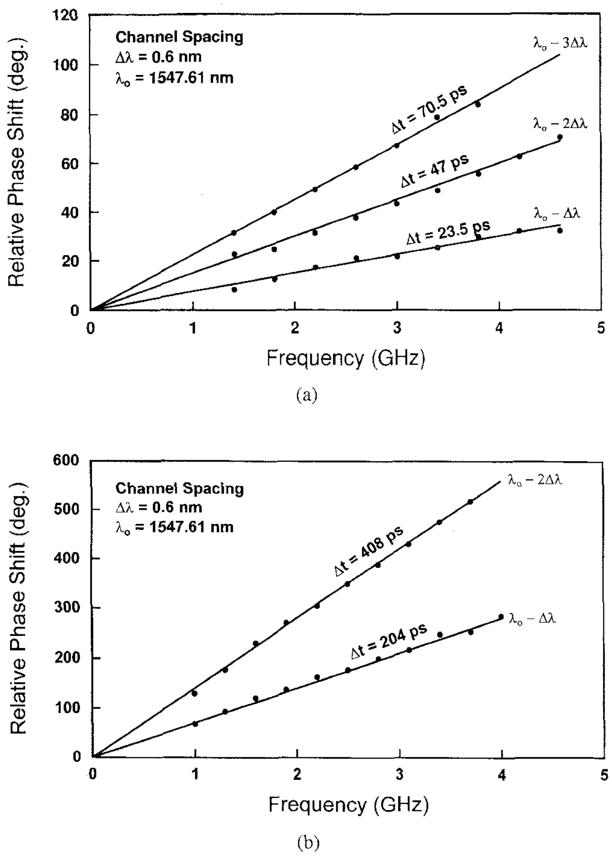


Fig. 4. Relative RF phase shift versus frequency for various channels relative to the reference channel at $\lambda_o = 1547.61$ nm. The total dispersions of the fibers are (a) 39.1 ps/nm, and (b) 340 ps/nm.

distributed feedback laser array chip with 18 equally-spaced channels has been reported [12] and even larger arrays are possible. Wavelength re-use in conjunction with multiple PDM's can be employed to further multiply the array size. In this case, each PDM is attached to a subarray of the entire antenna system. For two-dimensional arrays, cascaded approaches similar to those in [5], [6] can be adopted. Alternatively, as described in [4], we can avoid the optical/electrical/optical conversion by feeding the processed elevation signal to $m_{\rm col}$ (= number of columns) parallel wavelength-independent switched optical delay lines for azimuth control. The outputs are then sent to antennas through $m_{\rm col}$ WDM demultiplexers. This scheme requires one multiwavelength laser, one modulator, one PDM, and $m_{\rm col}$ switched optical delay lines. Comparing with the similar cascading approach employing tunable laser source [6], the multiwavelength scheme will dramatically reduce the number of required switched optical delay lines (by a factor of $m_{\rm row}$, the number of rows).

High-speed beam forming is possible by using EO switch that has a typical switching time of less than 1 ns at the expense of higher optical insertion loss. The total dispersions of the fiber segments in PDM need to be properly matched to ensure accurate scanning angle. However, mismatch of the fiber length will not degrade the radiation patterns or the beam quality because all the wavelengths and hence RF signals travel through the same fiber.

In conclusion, we have proposed and experimentally demonstrated a hardware compressive programmable-dispersion matrix for true time delay in a MWOCPAA system. The MWOCPAA with m antenna elements and n-bit resolution can be realized with only one multiwavelength laser, one PDM comprising $(n+1)$ 2×2 optical switches and n dispersive elements, and a WDM demultiplexer. The unique "wavelength $\leftrightarrow$ array element" mapping eliminates the splitting loss associated with signal distribution. The scanning speed depends on the switching mechanism of the optical switches and can be as fast as 1 ns. The proposed system can also be scaled up in array size or time resolution with minor modification of the optical beam forming network.

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