OPTICAL BEAMFORMING NETWORK BASED ON CHIRPED FIBER GRATINGS CONTINUOUSLY VARIABLE TRUE-TIME-DELAY LINES

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ABSTRACT

A novel approach of true-time delay optical feeder for phased-array antennas is proposed and demonstrated. A compact size continuously variable true time delay unit is achieved by employing a reduced tuning-range tunable laser and one wide bandwidth chirped fiber grating as dispersive element. The dispersion-induced distortion and bandwidth limitation have been studied and two different optical modulation schemes (AM, SSB+C) have been considered and measured, proving to solve the mentioned effects. A high resolution performance (5.3 ps) is obtained employing narrow tuning bandwidth lasers with a wavelength stability of 0.005 nm and a 4 nm bandwidth chirped grating.

I INTRODUCTION

Optics offers many advantages for phased array antennas (PAA). Expected features for a phase shift element in a PAA would be size compactness, low losses, continuous variability, true time delay (TTD) and broad bandwidth. Phase shift selection based on wavelength-switching has been proposed by using dispersive fiber [1-2] to generate relative time delay among the optical wavelengths. Non-chirped Bragg fiber gratings have also been used as wavelength-selective time delay elements [3]. Instead of using several short gratings at different discrete positions, we propose a TTD optical feeder scheme that employs only one wide bandwidth chirped grating. In this approach, since each wavelength is reflected at a different position along the grating length; by tuning the laser wavelength, the time delay is selected on an almost continuous way. Recently, a very wide bandwidth (4 nm) chirped grating has been fabricated [4] which will allow many array antenna elements as well as moderate wavelength tolerances for the lasers.

II TIME DELAY UNIT

The use of chirped fiber gratings (CFG) as time delay lines has been recently proposed [5], showing their potential wide-bandwidth and continuous variability. Likewise, CFG have been demonstrated as continuously variable true time delay elements in optically controlled beamforming phased-array antennas [6]. In these schemes, the time delay for the RF signal can be continuously varied by sweeping the optical carrier wavelength of a tunable laser. The required laser tuning range may be very narrow if a high dispersion CFG is employed [6].

The main limitation introduced by CFG as a wide bandwidth TTD unit is the RF power degradation due to chromatic dispersion. In conventional intensity modulation/directly detected (IM/DD) schemes using external modulation, biasing is set at the quadrature point and the RF signal drives the Mach-Zehnder modulator (MZM), in such a way that an almost AM signal is achieved. After passing through the CFG, each sideband suffers different delays, proportional to the frequency separation and the CFG group delay slope δ(ps/nm). When this time delay difference is exactly a radiofrequency period, a destructive interference between both sidebands is produced at the receiver, canceling the microwave signal output. The lowest frequency at which the detected RF power falls -3dB is defined as the signal bandwidth, given by [6],

$$f_{max} = \sqrt{\frac{c}{4 \cdot \lambda_c^2 \cdot \delta}} \qquad (1)$$

The dispersion-induced RF degradation may be overcome by using single sideband plus carrier (SSB+C) modulation [7].
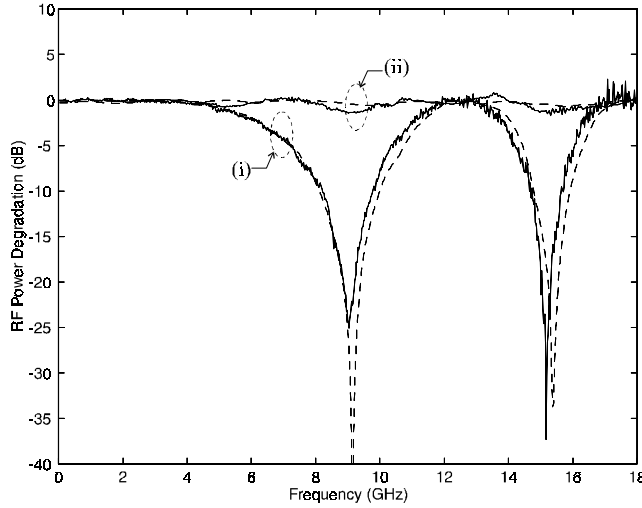
Figure 1.- RF Power degradation measurements and simulations from grating measurements (AM and SSB+C modulations, IM/DD scheme). (i) Solid line: AM IM/DD measurements. Dashed line: AM IM/DD simulation. (ii) Solid line: SSB+C IM/DD measurements. Dashed line: SSB+C IM/DD simulation. (m_o=0.1 and λ_o=1547.5nm)

The SSB+C generator may be implemented employing a dual-drive MZM. After passing through the CFG, the electrical intensity at the photodetector output shows no power degradation.

Figure 1 shows both simulation and experimental results obtained for the RF response of a CFG based time delay unit with a 40cm long CFG (δ of nearly 850ps/nm from 1547nm to 1551nm and 800ps/nm around 1547.5nm). The CFG dispersion-induced impact on the microwave bandwidth of a CFG-based time delay unit with AM modulation is clearly demonstrated from figure 1. On the other side, it can be seen that the SSB+C scheme provides an excellent mitigation of the CFG dispersion-induced RF degradation, increasing the bandwidth of CFG-based time delay units. The ripple shown in the experimental results in figure 1 is due to the actual ripple in the CFG group delay slope.

III BEAMFORMER ARCHITECTURE

The transmitting setup of the proposed TTD optical feeder is sketched in figure 2. A wavelength-to-array-element correspondence is used. The output lights from N narrow tuning bandwidth tunable lasers (λ_1 to λ_N) are combined and all the optical wavelengths are modulated by the same microwave signal employing an external electro-optic Modulator (EOM). The modulated lightwaves pass through an optical circulator to a long (several centimeters) wide bandwidth CFG. The resonance position inside the CFG, i.e. the reflection point, depends on the wavelength according to the selected chirping law. If a linear chirp is chosen, the relation between the reflection position and the wavelength is linear, and so is the round-trip delay. The N delayed modulated lightwaves (λ_1 to λ_N) are finally separated by means of a wavelength-division-multiplexed (WDM) demultiplexer and then passed to each antenna element after photodetection (PD).

Beam steering is achieved by lasers wavelength tuning. The maximum delay ($\pm\tau_{max}$) needed on each element will depend on the antenna element spacing (d) and the maximum scanning angle ($\theta_{max-scan}$). An extra standard single-mode fiber length (L_i) needs to be added to each antenna element branch in order to compensate for the time delay at the corresponding center position wavelength (λ_i).

The wavelength excursion needed at any laser depends on the maximum expected time delay and the grating group delay response (ps/nm),

$$\Delta\lambda(nm) = 33.3 * \frac{(N-1)*d(cm)*sin(\Theta_{max-scan})}{\delta(ps/nm)} \quad (2)$$

Assuming a separation between adjacent wavelengths of one and a half times the used bandwidth and a constant group delay slope, the maximum number of different-delay addressable antenna elements employing a chirped fiber grating with a total bandwidth $\Delta\lambda_{CFG}$ is,

$$N_{MAX} \approx \sqrt{\frac{\Delta\lambda_{CFG}(nm)*\delta(ps/nm)}{50*d(cm)*sin(\Theta_{max-scan})}} \quad (3)$$

IV FIRST EXPERIMENTS

In order to demonstrate the principle previously described, a four elements PAA has been considered. The experimental setup corresponds to a single branch of the general scheme in figure 2.
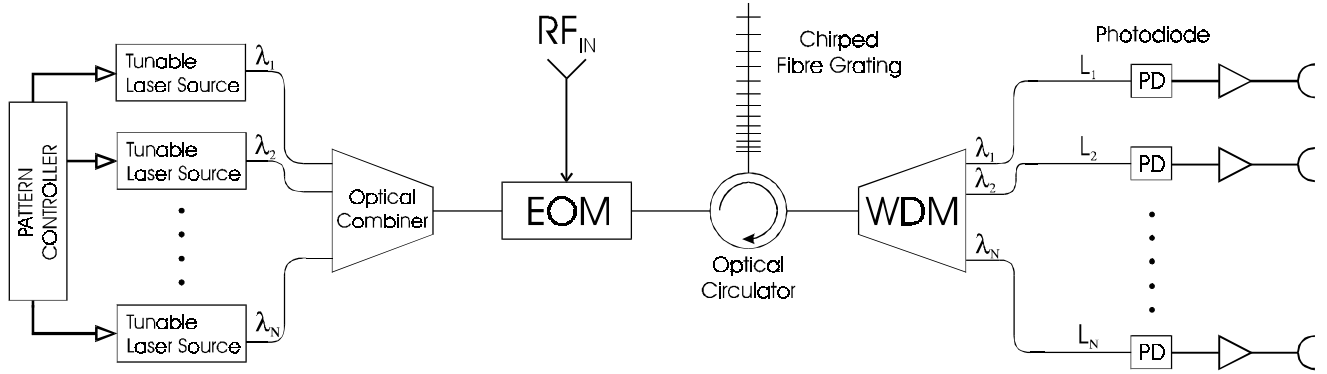
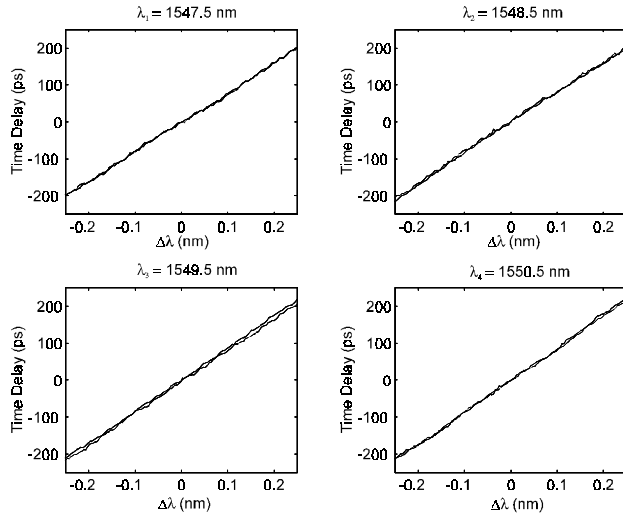Figure 2. True Time Delay Beamformer Transmitting Mode Block Diagram.

Figure 3. Time Delay measurements at each antenna element for two different microwave frequencies (2 and 5 GHz) as a function of deviation from central wavelength (Δλ). Each figure corresponds to a different wavelength.

The CFG employed is a 40cm long tapered linear CFG with a linear group delay response within a 4nm bandwidth ($\Delta\lambda_{CFG}$ =4nm) around 1549nm. The mean group delay slope is 835 ps/nm. We will assume N=4, d=4cm and a full scanning range (±90°). A maximum delay (τ_{max}) of 200ps and a wavelength excursion (Δλ) of nearly 0.5nm are obtained. The values for the center wavelengths were: λ_1=1547.5nm, λ_2=1548.5nm, λ_3=1549.5nm and λ_4=1550.5nm. The time delay for the full CFG bandwidth were measured at two different microwave frequencies, 2 and 5 GHz. The compensating length (L_i) and the group delay slope (δ_i) for each laser/element branch were extracted from these measurements. Taking into account a 0.5nm. bandwidth around each λ_i the following results were obtained: L_1=0cm,

δ_1=796ps/nm, L_2=16.94cm, δ_2=821ps/nm L_3=34cm δ_3=856ps/nm L_4=51.55cm, δ_4=865ps/nm. The compensated time-delay measurements for each element (around each λ_i) for both microwave frequencies are depicted in Fig. 3, proving to be almost linear and independent of the RF frequency. Fig. 4 shows the time delay results that will be obtained at each antenna element for an input RF signal of 5GHz as a function of the steering angle, considering that each laser is driven according to the measured slope (δ_i). The theoretical results are also displayed in Fig. 4, showing a very good agreement with the experimental results.

To estimate the total system time delay error two main causes are assumed: the laser wavelength stability $\Delta\lambda_{LASER}$, and the deviation from the CFG time-delay linear slope σ_{SLOPE} estimated over the bandwidth around each center wavelength. The results for the total system time precision (σ_{TOTAL}) assuming a laser wavelength stability of 0.01nm are shown in Table I. The total system time delay precision is 8.94ps (equivalent to a 16.1 degrees phase error at 5GHz or 6.4 degrees at 2 GHz).

Table I. Time delay deviation from linear response (δ_i).

σ_{TOTAL}	λ_1(nm) 1547.5	λ_2(nm) 1548.5	λ_3(nm) 1549.5.	λ_4(nm) 1550.5.	Mean σ
2 GHz	8.79 ps.	9.05 ps.	8.94 ps.	9.50 ps.	9.10 ps.
5 GHz	8.36 ps.	8.82 ps.	8.82 ps.	9.08 ps.	8.77 ps.

In this experiment, the time delay error comes mainly from the laser wavelength stability. A laser stability reduction to half its value ($\Delta\lambda_{LASER}$= 0.005nm) provides a total time delay rms error value of 5.2ps (3.8 degrees phase rms error at 2GHz).
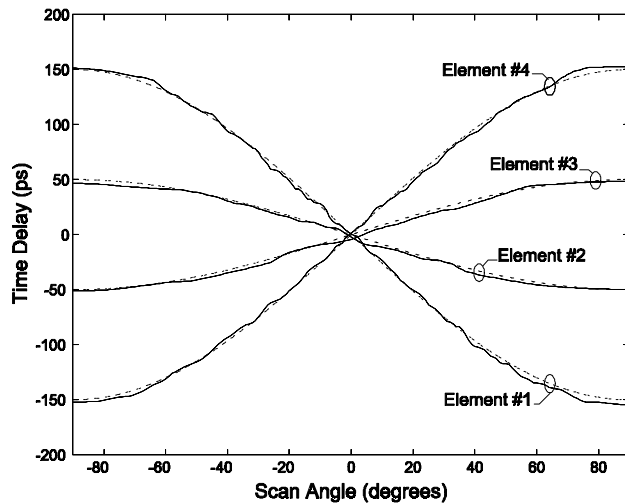
Figure 4. Time delay measurements (dashed lines) and theoretical results (solid lines) as a function of the scan angle when f_{RF} = 5 GHz.

VI REMARKS AND DISCUSSION

The results obtained confirm the expected performance employing the proposed optical beamforming scheme. Those results may be improved with specifically tailored fiber gratings with very low group delay response ripple. Opposed to previously proposed optical beamformers that employ only one broad bandwidth tunable laser or one fixed multiwavelength source, the approach presented allows any possible antenna elements phase distribution, not just linear phase, making it suitable for advanced PAA features.

The N tunable lasers bandwidth requirement is just some tenths of nanometre. Semiconductor Photonic Integrated Circuits with several tunable lasers (2.5nm tuning range) are currently available [8], reducing considerably the beamformer size and cost. Using just one grating for the whole system is a clear advantage since mismatches in the numerous gratings may result in important inaccuracies. The maximum number of antenna elements for the proposed beamformer is currently limited to few tens, for frequencies between L-Band an X-band.

VII CONCLUSION

The bandwidth limitation on the use of CFG as broad bandwidth time-delay units in IM/DD optical systems is shown. Measurements of a 40cm long CFG with high dispersion (850ps/nm) confirm the expected results. SSB+C modulation on IM/DD systems is proved to allow radiofrequency independent continuous time-delay variation.

A continuous TTD beamformer with one wide bandwidth CFG, suitable for arbitrary array phase distribution has been shown. A 40 cm long chirped fiber grating has been used as the only dispersive element of the system, and it has been proved to potentially drive a 4 elements wide-bandwidth PAA with high resolution. Inaccuracies due to the wavelength stability of lasers and the linearity of the chirped grating group delay have been considered.

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