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Wide Bandwidth LFM Transmission through a Wavelength-controlled Photonic True Time Delay Device

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***Abstract*-We demonstrate for the first time high quality wide bandwidth (600MHz) LFM transmission through a wavelength-controlled photonic True Time Delay device with bandwidth-limited resolution and peak sidelobe level below -37dB @ 5GHz.**

I. INTRODUCTION

Photonic beam formers are being considered for wideband RF true time delay (TTD) systems using linear frequency modulated (LFM) waveforms. The major criteria being studied are loss, *s/n* and spectral purity[1]. In receive, the feasibility of optical links are presently limited by inter-modulations and the need for large dynamic range. Moreover, the trend for wideband radars is to use digital receivers on the sub array level. However, in transmit the link can work at high modulation indices, alleviating several of the difficulties in practical implementations. Several schemes for photonic TTD have been suggested over the years, including dispersive fibers [2], wavelength routing via an AWG multiplexer[3] and chirped Bragg gratings [4]. In this paper we propose and demonstrate wideband, high quality LFM transmission using a wavelength-controlled photonic TTD implementation

Following a theoretical discussion of distortion mechanisms in LFM transmission, Section II, the photonic TDD is described in Section III and its transfer function is experimentally characterized in section IV. Finally, the results of the 600MHz LFM transmission at 5GHz are presented in Section V, followed by some discussion and conclusion.

II. THEORY

A. The effect of the RF transfer function on LFM transmission

An ideal LFM square pulse at the input of a transmission system is defined by

$$E_{in}(t) = \cos\left[2\pi f_0 t + \frac{B}{2T}t^2\right]\mathrm{rect}[t/T], \qquad (1)$$

where f_0 is the pulse center frequency, B is the total bandwidth of the signal and T is the pulse length.

During the pulse life $(-T/2 \le t \le T/2)$, the instanteneous frequency $f(t) = f_0 + (B/T)t$ linearly spans the frequency range $f_0 - B/2 \le f \le f_0 + T/2$. There is thus a mapping [5] between the instantaneous frequency and time in the pulse so that when the LFM pulse goes through a non-linear device it will produce harmonics but not intermodulations, which limit *s/n* and dynamic range. The Fourier transform of $E_{in}(t)$ is approximately given for BT>100 by

$$\Im[E_{in}](f) \propto \exp\left[-j\frac{T}{2B}(f-f_0)^2\right]\mathrm{rect}\left[(f-f_0)/B\right] \qquad (2)$$

If the RF transfer characteristics between the input and output of the transmission link can be described by the linear RF filter $H(f) = A(f)\exp[j\phi(f)]$, then the received signal is the inverse Fourier transform of the product of $H(f)$ and the spectrum of the input LFM signal:

$$E_{Rec}(t) \propto \Im^{-1}\left[\Im[E_{in}](f)H(f)\right] \qquad (3)$$

The signal then undergoes correlation with the undistorted pulse either via weighted matched filter processing or dechirp processing [6]. This process removes the parabolic phase and through the use of the inverse Fourier transform produces a narrow output temporal pulse whose width is inversely proportional to B. For an $H(f) \propto \exp[-j2\pi f t_d]$, representing a pure time delay of t_d and a matched filter with uniform magnitude, the ideal temporal output follows a sinc function with a very narrow main lobe but with rather high sidelobes[6]. Therefore, in many systems a weighting filter is used to substantially lower the level of the time sidelobes at the expense of somewhat broader main lobe. In practice, $H(f)$ deviates from a pure time delay, and the actual frequency dependence of its amplitude and phase, $A(f)$ and $\phi(f)$, define what time resolution and sidelobe level are achievable by the system.

For a single periodic ripple-like error, having a period of P Hertz, three cases can be distinguished:

1) The period P is much larger than B.
2) The period P is much smaller than B.
3) The period P is of the order of B.

In the first case, the error is usually expanded in frequency and approximated by a quadratic function, which will cause a broadening of the correlation peak. In the second case, the periodic function will cause a sidelobe, the level of which is defined by the magnitude of the ripple and its position relative to the LFM central frequency f_o [6]. When both amplitude and phase ripples exist simultaneously, the deleterious effects are harder to classify as the sidelobes can become asymmetrical depending on whether the amplitude and phase ripples are in phase or in quadrature. Quantitatively, for $B/P<1$, the main beam is widened and the sidelobe level remains unchanged. As $1<B/P<2$, a skirt is formed around the main beam. For $B/P>2$, a distinct sidelobe appears. These types of errors have been rigorously analyzed both for radar systems and in antenna theory [7].

B. LFM related distortions in a photonic link

A photonic link comprises three basic modules: a modulator with its driving circuitry to convert the electrical signal into some form of modulation of the optical carrier (E/O), an optical device which transmits/processes the signal in an advantageously prescribed way and a photoreceiver (O/E) to retrieve the processed RF signal. An equivalent RF transfer function can be established from the RF input to the modulator circuitry to the output of the photoreceiver, and the impact of any deviations from a flat gain and linear phase on LFM performance can be studied using reference [8][6]. In practice, two sources of errors are to be expected: those which occur in the E/O and O/E conversions, and those which are purely optical in nature as determined by the *optical* transfer function of the optical device (the wavelength demultiplexer and its optical circuitry in our TTD implementation, see Sec. *III*)[8].

III. THE PHOTONIC TTD DEVICE

An 8 channel thin film optical demultiplexer (channels 23-37 on the ITU grid) was used to accomplish the wavelength-controlled TTD operation, see Fig. 2. The input RF sub-carrier modulated light went through a circulator and depending on its wavelength was routed to a particular output port, where a different length of fiber was spliced, having a highly reflective (~100%) silver coated tip, with a 0.5cm (50psec of round trip) increment from port to port. Thus, the returned light emerging from the circulator into the photoreceiver experiences a dispersion-free, wavelength–controlled pure delay. Fig. 2 also shows the experimental set up used for characterization. To ensure maximum *s/n*, the RF signal driving the $LiNbO_3$ modulator was electronically amplified so that the modulation index approached unity. Furthermore, the optical signal was amplified using an Erbium doped fiber amplifier (EDFA) to compensate for optical losses and to bring the optical signal at the input of the O/E, to the maximum unsaturated power (5dBm), tolerated by the receiver, thereby minimizing its associated shot and thermal noise contributions. The receiver itself had a trans-impendence amplifier (conversion gain of ~1000 V/W). The RF power level at the output of the photoreceiver was ~10dBm and the *s/n* was better than 75dB/MHz (for modulation index ~ 1). In our set-up the limiting factor was the laser RIN, although for a laser with improved RIN, the *s/n* will be dominated by the ASE of the optical amplifier to levels approaching 90dB/MHz.

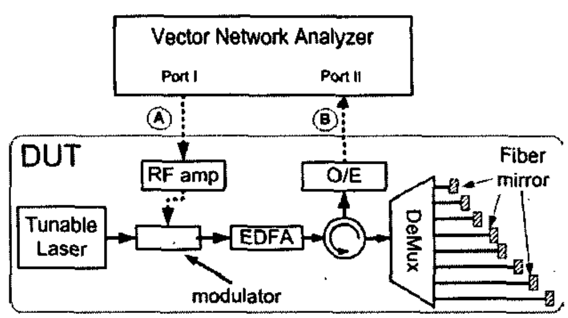

Figure 2: The DWDM based TTD and the experimental set-up for characterizing its magnitude and phase ripples.

IV. CHARACTERIZATION RESULTS

A vector network analyzer was first calibrated between the points A & B of Fig. 2. Thus, the measured RF transfer function of the DUT includes all RF and optical components. Alternatively, we also calibrated the vector network analyzer with the DUT present BUT with the EDFA, circulator and demultiplexer replaced by a short piece of fiber. This alternative calibration allows us to isolate the effects of our proposed photonic TTD, ignoring all the distortions in the E/O and O/E converters. Fig. 3 shows the normalized magnitude transfer functions for one of the 8 different time delays (different path lengths within the WDM) for both calibration methods.

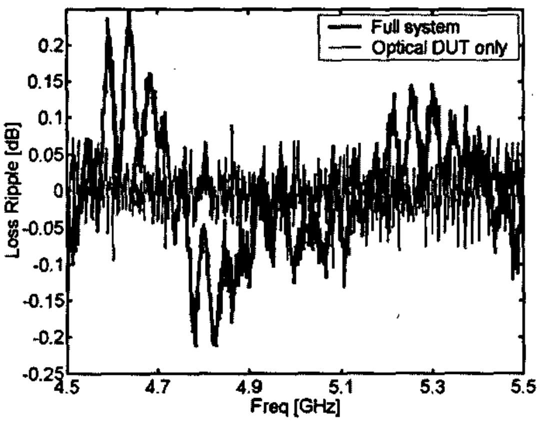

Figure 3: RF magnitude variations of the 1558.98nm wavelength through the photonic TTD device.

The magnitude variations are within ±0.25dB for the full system but less than ±0.05dB when the effects of the E/O and O/E are calibrated out.

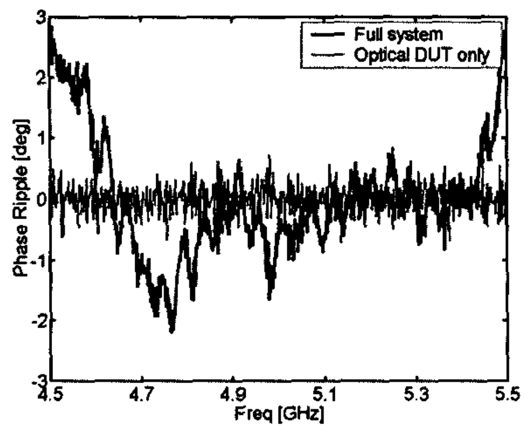

Figure 4: RF phase variations of the 1558.98nm wavelength through the photonic TTD device.

In Fig. 4, we display the phase ripple for the same channel for both calibrations. The measured phase ripple for the full system is ±3 deg. Again, a ten fold improvement in ripple to less then ±0.3 deg is obtained once the effects of the E/O and O/E are factored out. Almost identical results have been obtained for all other wavelength channels.

V. LFM RESULTS

The experimental set-up is detailed in Figure 5. An LFM signal, Eq. (1) with f_0=5GHz and B=600MHz, is injected into the photonic TTD device. Once through the DUT the detected LFM signal is converted to an IF signal and then sampled using a fast A/D and digitally (software) processed according to the prescription of Sec. II, using correlation with an ideal LFM pulse (pure parabolic phase) and a weighting Hamming window.

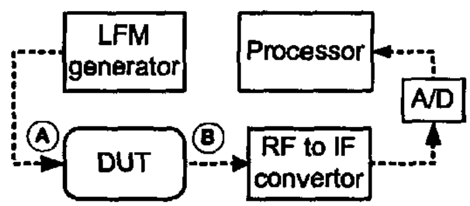

Figure 5: Experimental set-up for LFM characterization.

Fig. 6 shows the processed output pulse, also called the impulse response, where t=0 is artificially attached to the peak of the pulse.

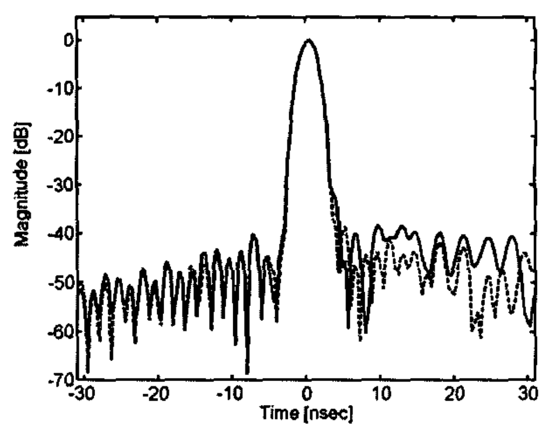

Figure 6: The output processed temporal pulse for a 600MHz-wide LFM signal. Dashed line: LFM reference measurement; Solid line: LFM through the photonic TTD.

First the LFM response is measured without the DUT *i.e.*, by bypassing the DUT in Fig. 5. This measurement yields the dashed line in Fig. 6. Next, the same signal is injected into the photonic TTD and its temporal output pulse is obtained (solid line in Fig. 6). Aside from a minute distortion of the main lobe at the -32dB level, all sidelobes, slightly modified from the reference case, have a peak sidelobe level (PSL) of less than -37dB down from the pulse peak. All other device wavelengths have been similarly checked, producing identical performance.

VI. Discussion

Wideband LFM signals are used in many RF applications to improve temporal resolution without the need to employ impractically high peak power short pulses. Maintaining flat RF transfer functions over wide bandwidth together with the need to steer antenna patterns (via phase shifters) is difficult using only RF circuitry. Our proposed design offers very wide bandwidth with extremely small magnitude and phase errors. Indeed, we have imposed the magnitude and phase distortions of the full system, Figs. 3-4, on a simulated ideal quadratic phase LFM signal (f_0=5GHz , B=600MHz) and applied the same processing algorithms. Fig. 7 compares the calculated LFM temporal response with and without the DUT introduced distortions.

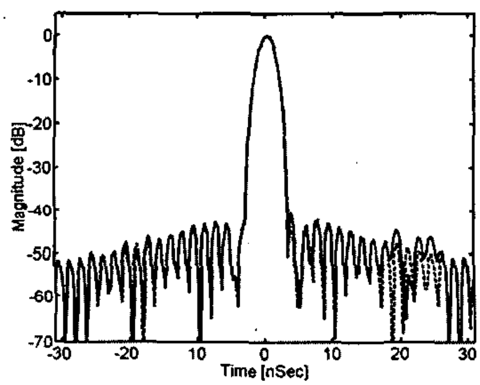

Figure 7: Simulated output temporal pulse for a synthetic ideal 600MHz-wide LFM input signal. Dashed line: Ideal LFM; Solid line: LFM response including the photonic TTD.

The PSL is seen now to be lower than -43dB/-40dB without/with the DUT. The results indicate that the performance in Fig. 6 is dominated by inherent distortions in the experimentally used input LFM pulse (dashed line in Fig. 6), as well as by RF connections with insufficient VSWR. In both Figures, though, the DUT introduced increased sidelobe activity around 20-25nS. This might be due to optical crosstalk, leading to multiple path interference (MPI), as described in [9].

VII. Conclusion

We have experimentally demonstrated that when a wide bandwidth LFM pulse goes through a DWDM based TTD photonic link, minimum pulse distortion occurs, while RF signal level and *s/n* remain at levels suitable for many radar applications. Further simulations based on network analyzer measurements suggest that LFM signals with even wider bandwidths (1GHz and more) can be transmitted with extremely low peak sidelobe levels and with time resolution commensurate with the bandwidth of the LFM input signal. It appears that most of the measured distortions in the overall RF transfer function of the photonic TTD stem from the E/O and O/E converters, so even better performance can be obtained with improved converters.

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