Time magnification of electrical signals using chirped optical pulses

F. Coppinger, A.S. Bhushan and B. Jalali

The authors report a method for stretching electrical signals in time. A high chirp rate is imposed on the electrical signal by mixing it with a dispersed ultra-short optical pulse in an electro-optic intensity modulator. This is followed by a passive optical dispersion element to produce a time-magnified copy of the input electrical signal.

Time manipulation of signals has been proposed as a possible technique to match the data rates of signals to the receiver or to observed very fast phenomena. Considering the time/space equivalence of dispersion and diffraction, and in direct analogy to a spatial lens, a signal may be stretched in time by subjecting it to a dispersion-quadratic phase modulation-dispersion sequence [1, 2]. While this concept has been known for some time, few successlul experiments have been carried out due to the difficulty of obtaining high quadratic phase modulation rate and/or large bandwidth dispersive elements. In his pioneering work, Caputi demonstrated an all-electrical time stretch system [1]. In the electrical domain, highly dispersive elements are available, however the small bandwidth of these elements limits the capability and performance of an all-electrical system. Large bandwidth dispersive elements are easily obtained optically, but the dispersion remains low requiring a high quadratic phase modulation rate (or linear frequency chirping). Resonant optical phase modulators were proposed as a way to attain a high modulation rate [3]. While high chirp rates are achievable with this device, the duration of the chirp is limited. Pulses from a Nd:YAG laser were also used to create the chirp in an all-optical time lens [2]. The time aperture of the lens was then limited by the bandwidth of the pulse (620GHz). In this Letter, we demonstrate an optoelectronic time magnification system with an electrical input/output and with the linear chirp provided by a dispersed optical pulse from a modelocked erbium-doped fibre laser (EDFL). In addition to the ultra-high bandwidth (~7.5THz) and chirp rate, this system differs from previously reported time magnification systems in that the bandwidth of the input signal is negligible compared to the chirp bandwidth. With this property, an approximation to an ideal time lens can be obtained without the need to disperse the input signal. This results in a more relaxed and simpler design of a time stretching system that can readily be implemented with commercially available components. This technique is promising for analogue-to-digital conversion of ultra-fast electrical signals.

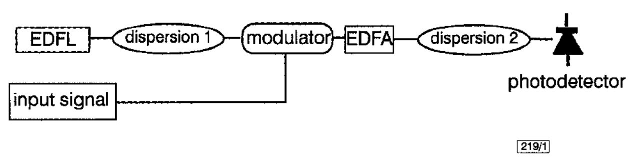

Fig. 1 *Experimental setup for time magnification using chirped optical pulse*

Fig. 1 describes our implementation of the optoelectronic time magnification system. The 160 fs pulse generated by the EDFL is dispersed in the input fibre. When the pulse reaches the modulator, different frequency components arrive at different times. The electrical signal to be stretched is efficiently mixed with the chirped optical signal by the Mach-Zehnder electro-optic modulator (12GHz bandwidth). The efficiency of the electro-optic mixing is significantly higher than optical-optical mixing [4] in a nonlinear crystal. The resulting intensity-modulated chirped signal is dispersed in a second spool of fibre and its envelope is detected by a fast photodetector with a 30ps response time.

In the experiment, we use a 2km spool of fibre to generate the frequency ramp. With a dispersion of 17ps/nm/km in the fibre, the chirp rate at the modulator is 3.5GHz/ps. To generate an arbitrary transient, we bias the modulator at V_π, and apply an electrical pulse to it. Fig. 2*a* shows the resulting waveform measured at the modulator output. It represents the applied electrical pulse, its second harmonic originating from biasing the modulator at V_π. The envelope is also somewhat shaped by the spectral envelope of the chirped pulse. The second dispersion consists of a 5.5km spool of fibre. Fig. 2*b* shows the intensity of the optical signal after propagation through the second dispersive element. The signal is stretched in time by a factor of 3.25 with high fidelity.

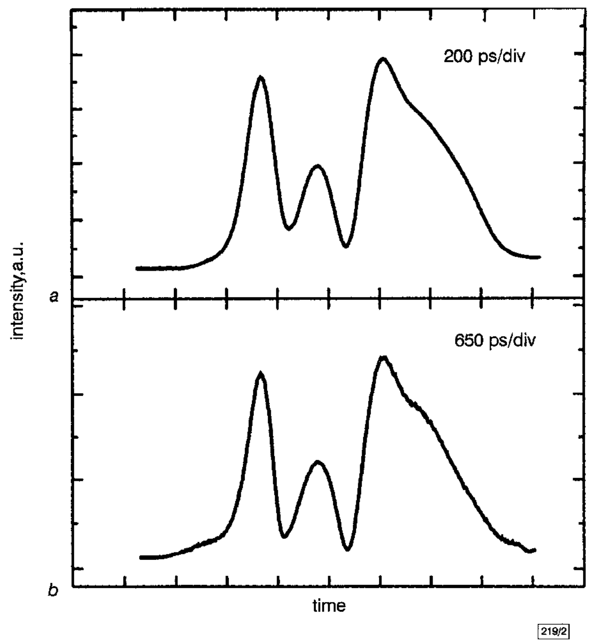

Fig. 2 *Signal envelope after modulation and magnified signal after second dispersion*

a Signal envelope after modulation
b Magnified signal after second dispersion

The magnification factor in our system depends on both the amount of dispersion in the second dispersive stage D_2 and the chirp rate. The magnification factor can be increased by increasing D_2 or by raising the chirp rate (decreasing D_1). However, increasing the chirp rate also reduces the time aperture of the system.

The fundamental resolution of a conventional fime lens in which the image is at the focal time of the lens is limited by its bandwidth and is estimated to be $1/B$, where B is the chirp bandwidth [5]. If the image is not at the focal time (the case in our experiment), the image will be distorted. However, the resulting distortion is negligible as the electrical signal bandwidth (~12GHz) is negligible compared to the bandwidth of the chirp (~7.5THz). Further, the distortion is averaged out by the finite response time of the photodetector as long as $\Delta f_e D_2 < \tau_{pd}$, where Δf_e is the bandwidth of the electrical signal and τ_{pd} is the response time of the photodetector (30 ps). The resolution and linearity of the lens are also limited by the non-constant dispersion inside the fibre over the spectrum of the EDFL. Dispersion-flattened fibre would mitigate this problem. The influence of the non-flat optical spectrum on the input signal can be minimised by spectrum equalisation using a fibre Bragg grating filter, dispersion decreasing supercontinuum fibre [6], or a feedforward architecture [7].

In summary, we have used the high chirp rate offered by a dispersed pulse from an EDFL to stretch an electrical signal in time. The frequency ramp is intensity modulated by the electrical signal in a Mach-Zehnder electro-optic modulator. The chirped signal is then further dispersed leading to time magnification. This technique has potential for the digitisation of high frequency electrical signals.

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Packaged array of eight MSM photodetectors with uniform 12GHz bandwidth

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Transmission line concepts were used in the design of a broadband, integrated photodetector array. The array consists of eight metal semiconductor-metal (MSM) photodetectors, with active regions of (26μm)², distributed along a common bus. A uniform 3dB bandwidth of 12GHz is demonstrated. These arrays are central to optoelectronic switching techniques, and are applicable to microwave fibre optic systems.

Introduction: Arrays in which several photodetectors drive a single broadband load are becoming increasingly important. They were originally conceived as part of the optoelectronic switching method [1], where they are used as column vectors in the construction of a cross-point switch or signal processor [2]. Metal-semiconductor-metal (MSM) photodetectors are particularly well suited to this application [3], due to their large bandwidth, large active area, simple planar structure, and low capacitance. In addition, their symmetry allows bipolar operation and implies good on-off isolation [2]. A second emerging application of photodetector arrays is in the microwave fibre optics field, where the link insertion loss and signal-to-noise ratio may be limited by the power-handling capabilities of photodetectors in the receiver [4, 5].

We report a bandwidth of 12GHz for an integrated array of eight top-illuminated MSM detectors, packaged on a dielectric carrier with coplanar waveguide access lines. To our knowledge, this is the highest speed reported for an array of detectors with individually accessible bias lines, as required for optoelectronic switching. Previously, Liu *et al.* [6] reported 5GHz operation for an array of 4 PIN detectors.

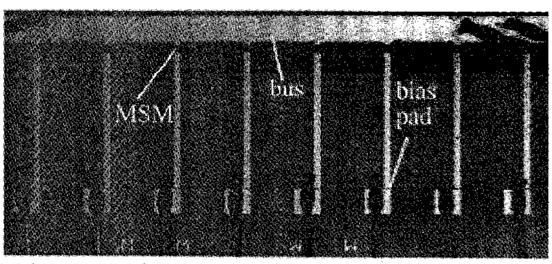

Fig. 1 *Photograph of packaged detector array*

Fabrication: Fig. 1 shows a photograph of the array reported here. Eight integrated MSM photodetectors, with (26μm)² active regions, are attached to a common bus, with an inter-detector spacing of 250μm. The opposite contact of each MSM provides individual bias control, so that the detectors may be selectively turned on or off. The arrays were fabricated on a nominally *n*-type GaAs epitaxial layer, with a carrier concentration of < 10^{14} cm^{-3}. Dielectric isolation layers were omitted, but the dark current was < 100nA at an operating bias (0–10V). The interdigitated electrodes have finger spacing and a width of 2μm. After dicing, the chips were mounted on dielectric carriers with RF, coplanar-waveguide access lines. The bias pad of each MSM was wire bonded to an AC ground via a bias decoupling capacitor. The common bus was connected to the coplanar lines on the chip carrier, via multiple wire bonds at each end.

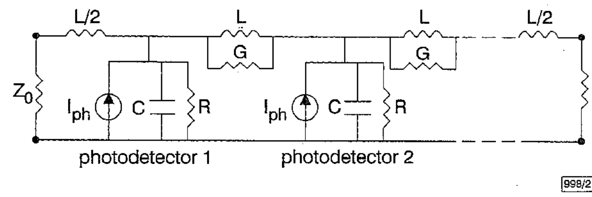

Fig. 2 *Simple equivalent circuit for array described in text*
Each end of array is terminated in system impedance

Theory: The basic theory of travelling-wave detector arrays is available elsewhere [5]. Essentially, the capacitance of a single long detector or several parallel photodetectors can be compensated by the inductance of an appropriate interconnect network, such that an artificial transmission line matched to the system impedance is formed. This is illustrated schematically in the lumped-element model of Fig. 2. The capacitance derives primarily from the photodetectors, the resistive loss terms are mainly due to finite conductivity and charge storage in the semiconductor layers, and the inductance is provided by an appropriate interconnect network, as mentioned.

At microwave frequencies, it is more accurate to treat the interconnecting lines with a distributed model. For the arrays discussed here, the interconnect network is provided by an on-wafer microstrip line, which forms the common bus. The bus is 100μm wide and 500μm from the ground plane. The impedance of this line is approximately 80Ω, and the effective propagation index is approximately 2.78. The photodetector array closely resembles a periodically loaded transmission line. The matching criteria for a terminated periodic structure are well-known, and lead to the condition [5]:

$$d_L = \frac{cZ_L C_d}{n_L\left[\frac{Z_L^2}{Z_0^2} - 1\right]} \qquad (1)$$

where d_L, Z_L, and n_L are the inter-detector length, characteristic impedance, and effective propagation index of the high-impedance interconnect, respectively. C_d is the capacitance associated with each photodetector, and Z_0 is the impedance of the external system. Eqn. 1 is valid for wavelengths greater than the period of the loaded-line structure.

The capacitance of discrete MSM photodetectors is often estimated using conformal transformation [7]. Those methods predict the capacitance associated with the interdigitated fingers only, assuming no excess charge storage in the semiconductor layers. In real MSM detectors, two other sources of parasitic capacitance must be considered. These are the capacitance associated with the bond pads and interconnect metal [7], and the so-called depletion capacitance [8] arising from charge storage deep in the semiconductor bulk or at heterojunctions. By forming these arrays on a resistive homojunction layer, grown on a semi-insulating GaAs substrate, the depletion-capacitance is minimised [7]. This simplifies the design of an impedance-matched array, since both the finger and bond-pad capacitance contributions may be predicted from layout geometry.

Experimental results: The capacitance of detectors (in the array) was determined using an on-wafer probe, and by fitting S_{22} reflection data to a simple equivalent circuit [7]. The capacitance was approximately 40–60fF, with little bias dependence. From eqn. 1, and using the high-impedance line characteristics mentioned above, the required detector capacitance for matching the array to a 50Ω system is 45fF. Assuming perfect matching (C_d = 45fF), the