High resolution time-to-space conversion of sub-picosecond pulses at 1.55μm by non-degenerate SFG in PPLN crystal

Dror Shayovitz[1], Harald Herrmann[2], Wolfgang Sohler[2], Raimund Ricken[2], Christine Silberhorn[2] and Dan M. Marom[1]

[1]Department of Applied Physics, Hebrew University of Jerusalem, Jerusalem, 91904, Israel
[2]Department of Applied Physics, The University of Paderborn, Paderborn, Germany
Author e-mail address: dror.shayovitz@mail.huji.ac.il, danmarom@cc.huji.ac.il

Abstract: We demonstrate time-to-space conversion of ultrashort optical pulses using sum-frequency generation in PPLN. An order of magnitude increase in conversion efficiency over our previous work was achieved, whilst maintaining a resolution factor of 90.

OCIS codes: (190.0190) Nonlinear optics; (320.0320) Ultrafast optics; (060.0060) Fiber optics and optical communications

Channel data rates in optical communications are reaching 100Gb/s, limited by the electrical bandwidth of optoelectronic components. Optical time domain multiplexing (OTDM) is able to overcome this limitation by passively combining multiple low bit-rate tributaries into a single high-speed serial channel. A recent demonstration of 10.2Tb/s data transmission achieved by 1.28Tbaud/s multiplexing together with 16-QAM [1] underlines the potential of OTDM for maximizing bandwidth efficiency by combining a high symbol rate and multiple bits per symbol modulation.

Time-to-space (T-S) conversion [2,3] is a nonlinear optical processing technique which utilizes sum-frequency generation (SFG) to convert a single serial OTDM channel to a number of slower parallel channels which can then be detected by an array of optoelectronic receivers. By bridging the gap between high-speed optical transmission and slower electronic detection capabilities, T-S conversion enables the implementation of OTDM detection at 1Tb/s bit rates and beyond. We have previously demonstrated high resolution T-S conversion in a BBO nonlinear crystal [2], but further progress requires a reduction in the T-S processor power requirements to a realistic level (tens of mW). Here we report an advance in this direction by employing periodically-poled lithium niobate (PPLN) as the nonlinear medium. The advantages of using PPLN for T-S conversion (high nonlinear coefficient d_{eff} = 16pm/V and absence of spatial walkoff) have already been identified [3], however we have implemented collinearly phase-matched SFG in PPLN thus increasing the interaction length up to the beam diffraction limit. The result is a large increase in conversion efficiency compared with our previous work, whilst maintaining background-free operation and high T-S conversion resolution.

Figure 1 shows our experimental setup. The signal and idler (reference) outputs of a Spectra-Physics Opal OPO (with pulse duration 100fs and repetition rate 80.2MHz) are expanded to appropriate collimated beam sizes and undergo opposite linear spatial dispersions of approximately 5mm over a 40nm (-3dB) bandwidth by diffraction gratings and 75mm lenses. The two dispersed beams are superimposed by a dichroic mirror and are incident on a PPLN chip located at the focal plane. The PPLN poling period is 20.5μm and the poling aperture in the spatial dispersion direction and length in the light propagation direction are 6mm and 19mm respectively. The crystal temperature is held at 135ºC to avoid photorefractive damage. The confocal length of the focused signal and reference beams in the plane of dispersion was 1.5mm (per spectral component), thus only a short section of the long crystal is utilized in practice. The relevant beam characteristics are listed in Table 1.

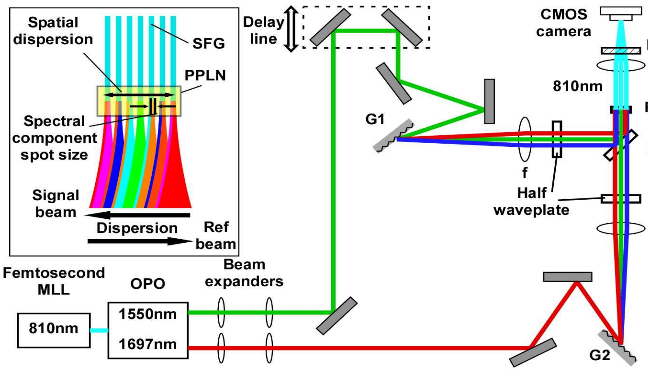

Fig. 1: Experimental setup (MLL, mode-locked laser; OPO, optical parametric oscillator; G1/G2, grating; f, Fourier lens; DM, dichroic mirror; PPLN, periodically-poled lithium niobate; BPF, band pass filter. Inset: Dispersed signal and reference beams at the PPLN.

Table 1: Input beam characteristics of T-S converter (λ_0: central wavelength, f_g: grating frequency, α: incidence angle on grating, dx/dω: spatial dispersion, w_0: focused spot radius of single spectral component, P_{av}/P_{max}: average beam power/peak power at the PPLN). Ideally the reference beam power would be higher than the signal power.

	λ_0 (nm)	**f_g (lp/mm)**	**α (°)**	**dx/dω (mm/THz)**	**w_0 (μm)**	**P_{av}/P_{max} (mW/kW)**
Signal	1500	1100	70.0	0.16	13	240/30
Reference	1697	1000	79.8	-0.16	14	64/8

Due to the matched yet flipped spatial dispersions of the signal and reference beams at the PPLN crystal, non-critically phase-matched SFG at each point in space results in a quasi-monochromatic output beam at 810nm. A lens of focal length 75mm coherently focuses the SFG light to a tight spot at the pulse image plane where a CMOS camera records the output spatial image (Figs. 2a and 2b); we placed a ND filter in front of the camera in order to suppress saturation. The SFG linewidth was measured as 0.14nm using light coupled by a multimode fiber into an optical spectrum analyzer (Fig. 2c). Note that this narrow linewidth (64GHz) implies the possibility for extraction of phase information from the converted signal by applying coherent detection techniques. Background second harmonic light from the signal and reference beams is blocked by a bandpass filter between the lens and the camera.

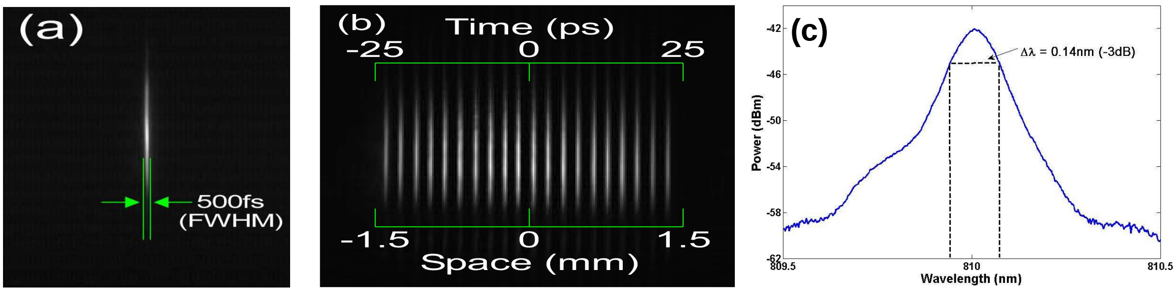

Fig. 2: (a) T-S converted signal pulse image with 500fs FWHM, (b) 20 spatial pulse images distributed throughout the T-S processor time window (composite image) and (c) SFG narrowband spectrum centered at 810nm with a −3 dB bandwidth of 0.14 nm (= 64 GHz).

The FWHM time window (which limits the maximum extent of the T-S converted spatial pattern) was measured by varying the delay line in the signal beam path. The conversion efficiency is defined as the SFG output power divided by the signal beam power incident on the PPLN and was measured by placing a power meter after the bandpass filter. The results are shown compared with those attained with a BBO nonlinear crystal [2] in Table 2.

Table 2: PPLN-based T-S conversion parameters compared with previous results using BBO reported in [2] (ΔT, FWHM time window; τ, FWHM pulse image width; N, serial-to-parallel resolution factor; η, conversion efficiency).

	ΔT (ps)	**τ (ps)**	**N (=ΔT/ τ)**	**η (%)**	**Conversion efficiency slope (%/W)**
PPLN	45	0.5	90	3×10^{-2}	5×10^{-1}
BBO	35	0.35	100	1×10^{-3}	1×10^{-2}

An order of magnitude increase in conversion efficiency and in the conversion efficiency slope compared to BBO was achieved. The PPLN chip used in this experiment was still not AR-coated, hence there is a ~15% reflection loss at the input and output crystal faces. In addition the limited poling aperture of 6mm results in reduced optical power available for the phase-matched interaction; this also causes the slight decrease in resolution. We are currently developing a customized (shortened and widened) and AR-coated PPLN chip in order to further increase the conversion efficiency and fidelity, en route towards practical T-S detection of optical waveforms in the lightwave telecommunication band.

[1] T. Richter, E. Palushani, C. Schmidt-Langhorst, R. Ludwig, L. Molle, M. Nolle and C. Schubert, “Transmission of Single-Channel 16-QAM Data Signals at Terabaud Symbol Rates,” J. Lightwave Technol. **30** 504-511 (2012).

[2] D. Shayovitz and D. M. Marom, “High-resolution, background-free, time-to-space conversion by collinearly phase-matched sum-frequency generation," Opt. Lett. **36,** 1957-1959 (2011).

[3] J.-H. Chung and A. M. Weiner, J. Lightwave Technol. **21**, 3323-3333 (2003).