Programmable High Resolution Broadband Pulse Shaping using a 2-D VIPA-Grating Pulse Shaper with a Liquid Crystal on Silicon (LCOS) Spatial Light Modulator

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Abstract: We demonstrate programmable spectral shaping with simultaneous broad-bandwidth(>40nm) and high-resolution(<4GHz) using a 2-D VIPA-Grating pulse-shaper with a LCOS SLM. The apparatus is capable of scaling to bandwidths of 100s of nm with sub-GHz resolution.

OCIS codes: (320.5540) Pulse Shaping; (320.7085) Ultrafast information processing

Femtosecond pulse shaping is a widely used technique with applications ranging from optical communications to coherent control of quantum processes [1]. The achievable complexity of shaped waveforms in conventional 1-D pulse shapers is usually limited by two reasons: (1) limitations of spectral dispersers, which typically have either broad operation bandwidth but coarse spectral resolution or high spectral resolution but limited operation bandwidth. (2) limited number of control elements, e.g., only up to several hundred pixels in 1-D spatial light modulators (SLMs). Here we overcome these limitations to demonstrate an apparatus which can achieve programmable shaping simultaneously over broad bandwidths with high spectral resolution. Our approach combines a high resolution, narrow band spectral disperser with a low resolution, broadband spectral disperser for two-dimensional (2-D) spectral dispersion within a pulse shaping configuration. The 2-D spectral disperser was demonstrated first for optical communication applications [2] and later applied for massively parallel frequency comb spectroscopy [3]. We have previously demonstrated a 2-D pulse shaper based on this approach to achieve high complexity waveforms with time-bandwidth product > 1600 (achieving shaping of 150 fs pulses over a 200 ps temporal aperture) [4]. However, the work in [4] was limited to fixed, photolithographically fabricated masks. Our current work is geared toward achieving programmability by using a 2-D liquid crystal on silicon (LCOS) SLM (which has ~ 2 million pixels) [5].

As the high resolution disperser we use the Virtually Imaged Phased Array (VIPA) which is a side entrance Fabry-Perot etalon which achieves spectral dispersion by multiple beam interference [6]. VIPAs have been shown to achieve sub-GHz spectral resolution in pulse shapers [7]. However as is the case with Fabry-Perot devices, a VIPA has a free spectral range (FSR) which may typically be a few 100GHz; hence for most ultrafast applications in which bandwidths are orders higher, spectral components separated by integral number of FSRs are dispersed to the same spatial location. We overcome this by using a diffraction grating aligned in a perpendicular direction to spatially separate out overlapping FSRs. Also, since now the frequency spread is 2-D, we can use 2-D SLMs which have millions of pixels - far exceeding the number of control elements available in 1-D geometries. In our current work we use a 2-D Liquid Crystal on Silicon (LCOS) phase-only SLM [5] to perform spectral amplitude shaping (via programmable polarization rotation plus a polarizer). However, it is possible to use a phase-only device to perform simultaneous amplitude and phase shaping using diffraction effects (for e.g. [8]), which we plan to pursue in future work. Here we would like to contrast our work from other 2-D pulse shaping configurations (for example [8, 9]) which still utilize a single spectral disperser and have not been aimed at increasing the time-frequency complexity.

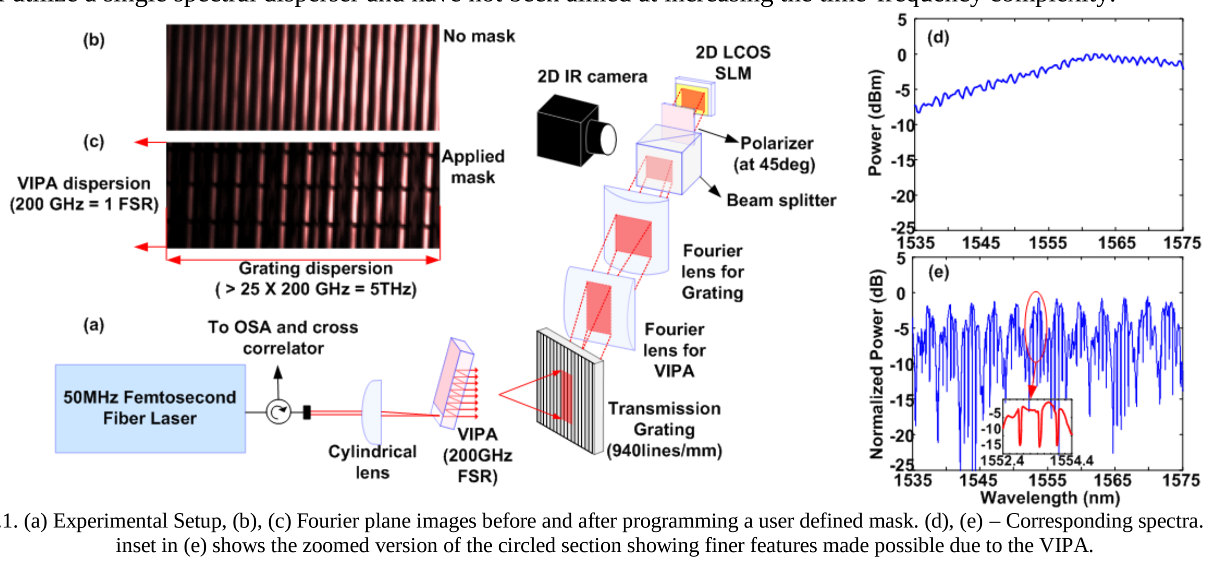

Fig.1. (a) Experimental Setup, (b), (c) Fourier plane images before and after programming a user defined mask. (d), (e) – Corresponding spectra. The inset in (e) shows the zoomed version of the circled section showing finer features made possible due to the VIPA.

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Fig. 1 (a) shows the experimental setup. Input pulses (110 fs centered at 1555 nm) from a passively mode locked Erbium fiber laser are first focused into the VIPA (200GHz FSR), then directed through a transmission grating with orthogonal dispersion direction, leading to a 2-dimensional spread of frequency components. Cylindrical lenses are used to focus the light onto the 2-D LCOS SLM placed at the Fourier plane. A 45° polarizer converts the SLM phase response into amplitude modulation. A 2-D IR camera images the Fourier plane to help with alignment and to visualize the masking process. Fig 1(b) shows the image of the Fourier plane without any masking function applied. Each vertical stripe corresponds to a different 200GHz spectral slice (equal to the VIPA FSR) separated by the grating. Fig 1(c) shows the modification at the Fourier plane with programming of the LCOS array, showing absence of various frequency components. Fig 1(d) shows the spectrum corresponding to the no mask case (1(b)) showing a relatively featureless spectrum (the curvature is representative of the actual laser spectrum). After the application of the mask, we have the spectrum shown in fig 1(e) (normalized with respect to the laser spectrum) showing a complex structure.

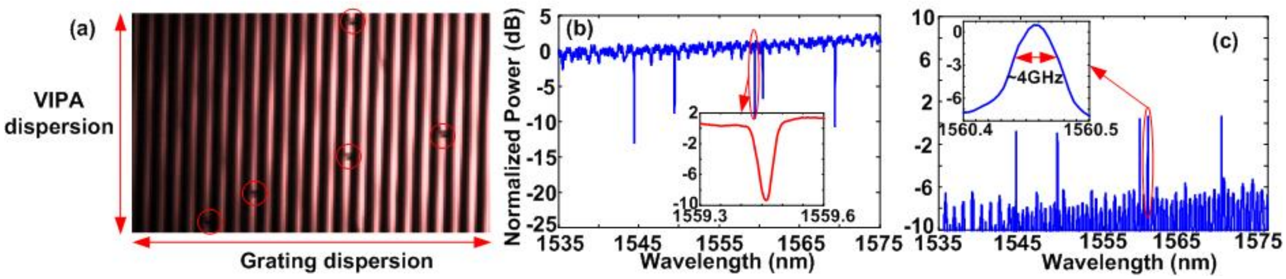

Fig.2. (a) Fourier plane image after programming a mask, which allows all but five wavelengths. These correspond to the dark spots circled in red. (b) Corresponding spectrum showing deep notches at the blocked wavelengths (inset shows a magnified version of one of the notches). (c) Spectrum obtained by programming the reverse mask, which allows none but five wavelengths (inset shows magnified version of one of the wavelengths, showing a 4GHz FWHM which corresponds to the spectral resolution of the pulse shaper.

Fig. 2 shows the results of an experiment to demonstrate high spectral resolution. The SLM is programmed to pass the entire spectrum except for narrow notches at 1544.5, 1549.5, 1559.5, 1561.5 and 1569.5nm. Fig 2(a) shows the Fourier plane image which has all the wavelengths except the blocked ones which are circled in red. Fig 2(b) shows the spectrum which is relatively flat except for the deep notches programmed. The inset shows the zoomed version of one of the notches. In fig 2(c) we show the spectra for the converse mask in which the same five wavelengths are now passed (remaining light blocked). The five selected wavelengths show up clearly as peaks. The inset shows a zoomed peak with width ~4GHz FWHM. In other data we have achieved spectral resolution down to ~3GHz. Note that by going to a VIPA with lower FSR (say 50GHz), sub-GHz resolution can be achieved if required. The total bandwidth is currently limited to ~40nm by the laser; however, the apparatus itself should be capable of handling 100s of nm.

In summary, we have experimentally demonstrated an apparatus which permits programmable control of fine spectral features over a large bandwidth. Our preliminary experiments here focus on spectral amplitude shaping. In continuing work we plan to utilize diffraction effects to simultaneously control both amplitude and phase using the phase-only LCOS-SLM and to characterize the resulting shaped waveforms in the time domain.

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