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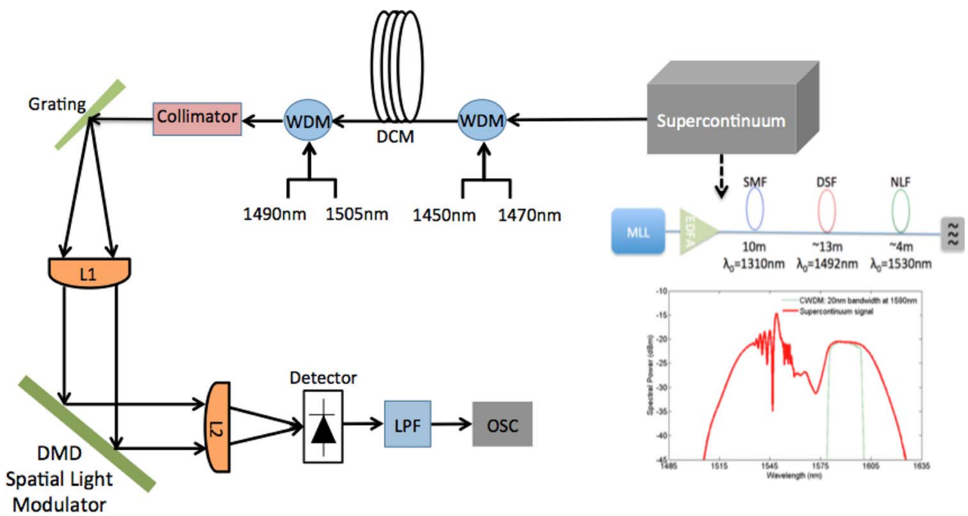

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Fast Arbitrary Waveform Generation by Using Digital Micromirror Arrays

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Abstract: We demonstrate fast optical arbitrary waveform generation by using the MEMS digital micromirror arrays. The desired radio-frequency waveforms are achieved by properly shaping the spectrum of the broadband optical source via using micromirror arrays as a digital spatial light modulator preceded by wavelength-to-time mapping through the dispersive medium. We obtain up to 280-MHz sawtooth and 200-MHz square waveforms that can be controlled by using 1024×768 mirror arrays in the preliminary experimental results. Based on currently available digital mirror technologies, we estimate that arbitrary waveforms up to 1-GHz rate and reconfigurable in $\sim$30 μs are achievable by using the proposed approach.

Index Terms: Microelectromechanical devices, microwave generation, spatial light modulators.

1. Introduction

Arbitrary waveform generators (AWGs) are highly desired in many areas such as wideband communication systems, instrument diagnostics, remote sensing, and radar applications. Optically assisted AWGs provide much better performance than the electronic AWGs in terms of the speed, bandwidth, and the dynamic range resolution [1], [2]. Various narrow-band techniques have been proposed to generate tunable RF waveforms by creating tailored pulse sequence through direct space-to-time mapping [3] and recombining time delayed pulses through RF interference via utilizing tunable laser diode source, electrooptic modulator, and dispersive fibers [4]. Beating of different longitudinal laser modes of wavelength-division-demultiplexed mode-locked laser (MLL) pulses also enables phase or amplitude modulation to produce arbitrarily shaped beat signals [5]. In addition, many approaches based on all-fiber techniques such as optical spectral shaping [6], microwave photonic filtering combined with wavelength-to-time mapping [7], and temporal pulse shaping via programmable amplitude-only [8] and phase-only modulation [9] have been recently proposed for optical waveform generation. Pulse shaping based on the space-wavelength mapping followed by a spatial mask or programmable spatial light modulator (SLM) has been widely established for femtosecond pulse shaping and programmable RF waveform generation [10]. Such RF AWG techniques using a direct space-to-time pulse shaper generating amplitude- and frequency-modulated RF waveforms up to 50 GHz [11] through high-rate tailored pulse sequences and a reprogrammable system producing waveforms up to 10 GHz [12] via frequency-to-time mapping have been previously proposed. In these spatial techniques, light modulation relies on the

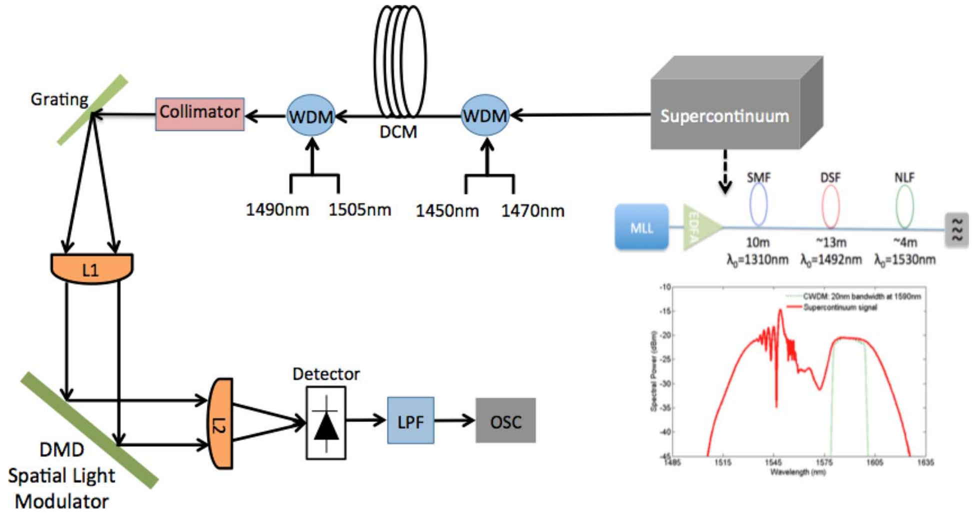

Fig. 1. Experimental setup for the all-optical arbitrary waveform generator (AWG). The inset figure shows the supercontinuum pulse generation and the achieved broadband spectrum. The nearly flat portion (20 nm centered at 1590 nm) is carved out by CWDM.

programmable liquid crystal horizontal pixel arrays that can control the amplitude and phase of the incident light, which are limited by the slow response on a timescale of milliseconds.

Recently, a new digital micromirror device (DMD) based on the DLP technology (Texas Instruments, Dallas, TX) enabling 2-D mapping and modulation via 2-D pixel arrays, high resolution, high reflection, exceptional stability, and excellent controllability over thousands of individual micromirrors has been commercialized. In comparison to most commonly used liquid crystal display (LCD) technology, such devices provide extremely faster switching speeds ($< 30\ \mu$s), less attenuation (higher fill factor of 90% than the LC with 70%), $\sim$6.6 times higher power transfer efficiency, $\sim$11 times higher contrast ratio, twice as higher diffraction efficiency of 88%, and feasibility for wide range of wavelengths [UV to near-infrared (NIR)] [13], [14]. The remarkable performance of such devices introduce them as a preferable alternative for digital SLMs, which can be used for programmable RF arbitrary waveform generation with considerably fast reconfiguration speed up to 32.5 kHz. Up to date, use of such devices for arbitrary waveform generation has not been utilized.

In this paper, we propose and demonstrate a new approach to generate optical arbitrary waveforms by using these MEMS-based digital micromirror arrays. In this preliminary experimental work, we demonstrate square and sawtooth waveforms at 200 MHz and 280 MHz by using 1024×768 mirror arrays, respectively [15]. By using the state-of-the-art MEMS technology, arbitrary waveforms up to 1-GHz rate and reconfigurable in $\sim$30 μs are achievable. Also, the prospect of DLP technology for high-speed AWG is discussed.

2. Experimental Setup and Results

The experimental setup for the proposed all-optical AWG is illustrated in Fig. 1. The system is mainly designed by combining broadband illumination, wavelength-to-time mapping, space-wavelength mapping, and spectral shaping modules [15]. As the broadband source, super-continuum (SC) pulses are generated by propagating the MLL pulses (at 1550 nm with $<$ 1-ps pulsewidth and 20-MHz repetition rate) through the amplifier (EDFA) and the cascaded single mode (10 m, $\lambda_0 = 1310$ nm), dispersion shifted ($\sim$13 m, $\lambda_0 = 1492$ nm), and nonlinear fiber ($\sim$4 m, $\lambda_0 = 1530$ nm) patch cords [16]. Bandpass filter (CWDM: Coarse wavelength division multiplexing) centered at 1590 nm is used to carve out the nearly 20-nm flat portion of the spectrum. Generated SC pulses are propagated through the dispersion compensation module (DCM with -675 ps/nm and $\sim$2.1-dB insertion loss) to map the wavelength information into temporal waveform for real time

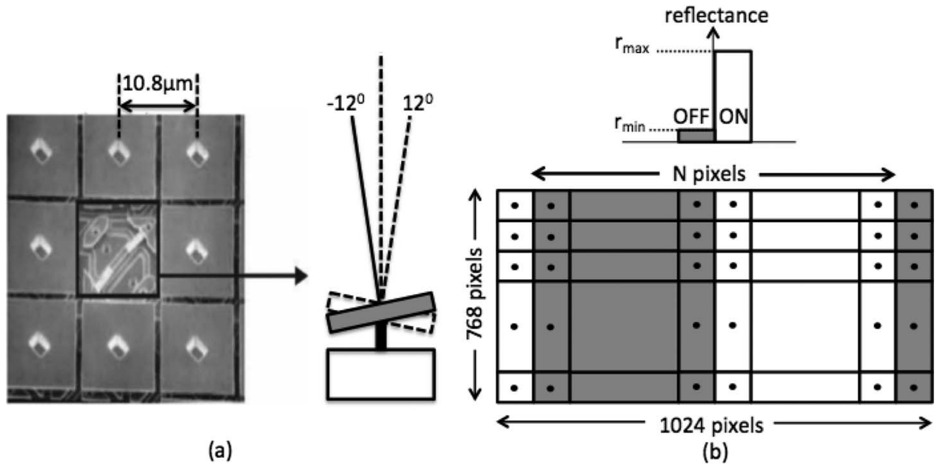

Fig. 2. Micromirrors integrated on DMD [18] with 10.8-μm pitch size and ~1-μm gap in-between can be oriented at either ON (+12°) or OFF (−12°) states (a). A sample implemented ON–OFF modulation pattern (b) on DMD [19].

detection. In order to compensate the system losses and to obtain better signal-to-noise ratio (SNR), flat gain Raman amplifier with ~10-dB net gain and <0.5-dB gain ripple is designed by using four high-power diode lasers at 1450 nm, 1470 nm, 1490 nm, and 1505 nm in a hybrid pumping configuration.

Temporally stretched SC pulses are spatially dispersed and collimated on to the DMD mirror array via diffraction grating with 600 lines/mm and cylindrical lens with 200-mm focal length, respectively. In order to focus the beam to have maximum spatial resolution, the diffraction grating and the DMD are placed 1-f distance from the first Fourier lens (L1) [17]. The DMD, 0.55-in diagonal mirror array, consists of 1024 $\times$ 768 individually addressable aluminum micromirrors with 10.8-μm pitch size and ~1-μm gap in between. Each mirror can be assigned to either ON $(+12^\circ)$ or OFF (-12°) states with high precision and speed to digitally modulate the light [13] [see Fig. 2(a)].

The DMD chipset used in the experiment can switch the states of the micromirrors with a rate up to 5 kHz. Recent DLP technology, on the other hand, has enabled the micromirrors to be re-configured up to 32.5 kHz with a fast switching speed of approximately 30 μs between the ON–OFF states, allowing for fast display of illumination patterns. The micromirrors having fill factor of 90% provide high optical efficiency and are capable of modulating broadband light ranging from ultraviolet to infrared wavelengths. The DMD mirrors are also protected by the cover glass, which is coated to operate for the desired spectral window [20]. Since the pulses are stretched in time, namely, the dispersive Fourier transform by the DCM, DMD-induced spatial modulation on the spectral domain is mapped into the temporal waveform and can be easily captured by a single photo detector and an oscilloscope. The spatially modulated pulses are focused by the second Fourier lens (L2 with f = 30 mm) in to the photo detector (> 1.2-GHz bandwidth). The detector is placed through the mirrors' ON-state direction. The DMD mirror array used in the experiment is protected by the cover glass, which is AR coated for visible light. Under broadband NIR illumination, strong interference results from the Fabry–Perot effect between the DMD mirrors and the cover glass. This spectral interference transforms to a temporal modulation by dispersive time stretching. As a result, a low-pass filter (LPF) with 1-GHz cutoff is used after the detector to eliminate this undesired interference. The detected unmodulated signal, in which all the mirrors are assigned to ON-state (white image pattern), and the etalon-induced interference, which occurs at ~1.8 GHz, are illustrated in Fig. 3.

In order to generate an arbitrary waveform, binary image patterns are created on the DMD to set the states of micromirrors accordingly to ensure the desired shape and the frequency [15]. The shape of the waveform corresponds to the image of the binary pattern. By carefully selecting the bandwidth of SC pulses, we can generate periodic waveforms encoded on a single laser pulse. On

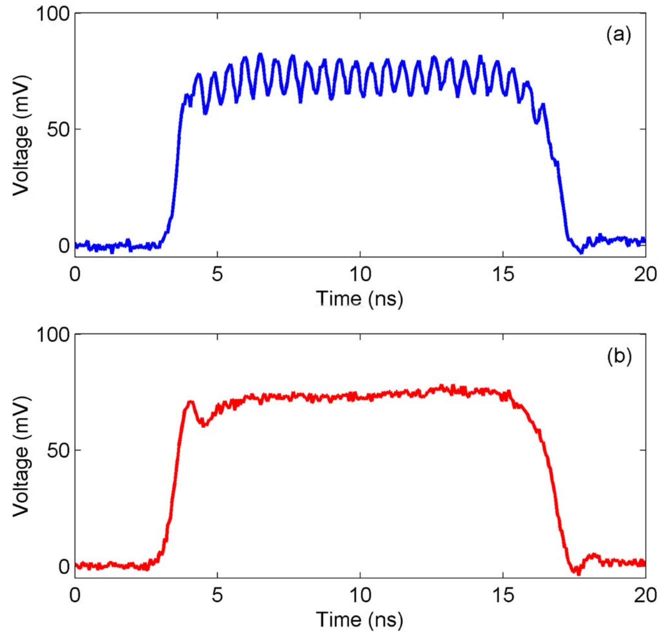

Fig. 3. Detected unmodulated signal (a) with ~1.8-GHz etalon-induced interference (a). Low-pass filter at 1 GHz is used to eliminate this undesired interference (b).

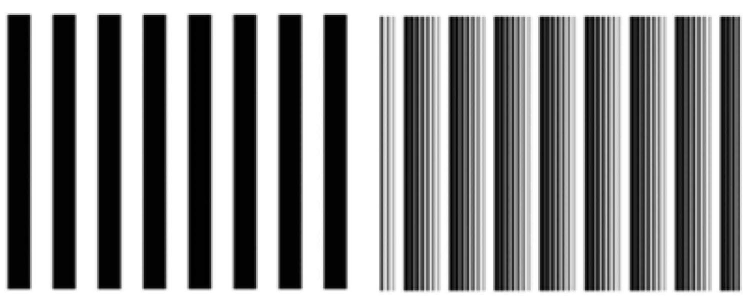

Fig. 4. Sample binary image patterns (128 mirrors/period) for generating square (a) and the sawtooth (b) waveforms.

the other hand, waveforms that appear longer period of time, namely, aperiodic with respect to laser repetition rate, can be achieved via using parallel system or utilizing different diffraction orders from the digital light mirrors.

Square waveforms are generated by using vertical-strip-like binary image patterns similar to the samples shown in Fig. 4(a). The black and white lines correspond to the OFF- and ON-states of mirrors, respectively. By adjusting the pattern spatial frequency and the duty cycle, different square waveforms can be obtained. As illustrated in Fig. 5, square waveforms with repetition rates ranging from 120 MHz to 580 MHz are generated for the proof of concept demonstration. Due to the spatial resolution of the optical system, as the pattern modulation frequency increases, the waveforms approximate to sinusoidal, rather than a square wave, through rounding of the edges [see Fig. 5(a) and (b)]. Increasing the spatial period of the patterns, namely, exceeding the diffraction limit, results in higher temporal modulation index and enables to achieve the desired waveforms with high accuracy in terms of the shape and the fine features [see Fig. 5(c) and (d)].

The DMD considered in the experimental setup can support up to 5-kHz binary and 500-Hz grayscale pattern rates. By properly setting the percentage of time the mirror is at ON-state, during

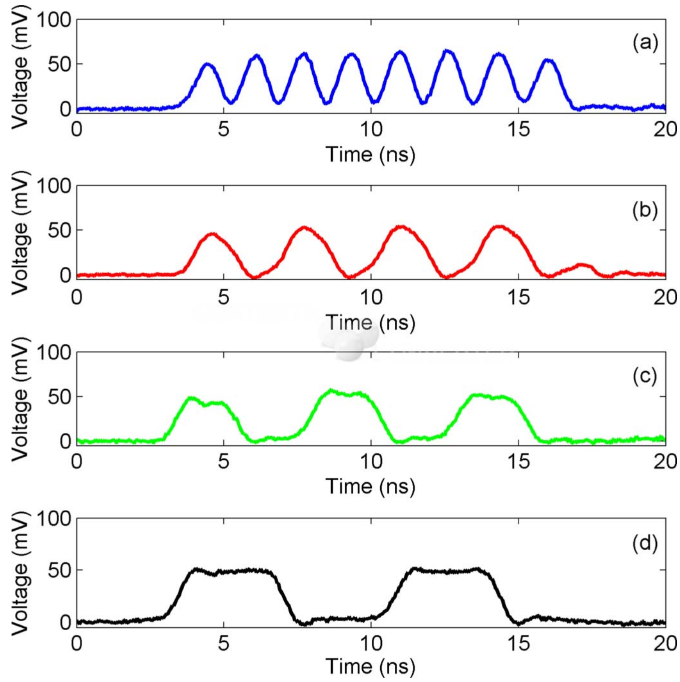

Fig. 5. Generated square waveforms with repetition rates of 580 MHz (a), 300 MHz (b), 200 MHz (c), and 120 MHz (d).

the refresh time, up to 256 (8-bit) grayscale intensities can be attained via averaging of dynamic patterns. However, since the temporal width of the SC pulses is much shorter than the DMD refresh time, the reflected light cannot be integrated to obtain the desired grayscale intensities. Thus, each mirror can only be assigned to either ON ("1") or OFF ("0") states through the static patterns. To enable amplitude modulation or to generate complex waveforms such as sawtooth or triangle, which include grayscale amplitudes, special binary patterns have to be created. We have proposed two different approaches to create such patterns to accomplish the amplitude quantization. In the first approach, since the DMD provides 2-D pixel arrays (1024×768), 2-D controllability over the modulator enables both the spectral shaping in one direction (horizontal) and the amplitude quantization in the other (vertical) direction. By expanding the beam vertically to illuminate the sufficient region over DMD, it is possible to adjust the number of vertical ON-state mirrors accordingly to set the quantization levels. In the second approach, the appropriate image patterns for the complex grayscale waveforms can be created by so-called pulsewidth modulation among the combined group of mirrors. The predefined modulation period (in terms of the pixels/mirrors) is divided into subperiods to enable the 1-D amplitude quantization. For each quantization level, the number of ON-state mirrors is set accordingly. To generate a sawtooth waveform, for instance, similar patterns shown in Fig. 4(b), which are created due to the second approach, are used. As illustrated in Fig. 6, three different sawtooth waveforms with repetition rates of 280 MHz [see Fig. 6(a)], 160 MHz [see Fig. 6(b)], and 120 MHz [see Fig. 6(c)] are generated for demonstration. The relative position of the space-wavelength mapping over the DMD pattern may cause irregularities such as the shearing and fading at the ends of the temporal window ($\Delta\tau \approx \Delta\lambda^*$dispersion $\cong$ 13.5 ns), in which the RF waveforms are generated. Since the MLL output rate is 20 MHz (50-ns period), there is $\sim$36.5-ns time gap (light power is zero) between each stretched pulse. This interval can be reduced or prevented either by increasing the temporal width of stretched pulse via using wider spectral width and longer dispersion compensating module or using such a parallel interleaved configuration with appropriate delay lines to perform a real continuous time operation. In this manuscript, we focus on single channel application.

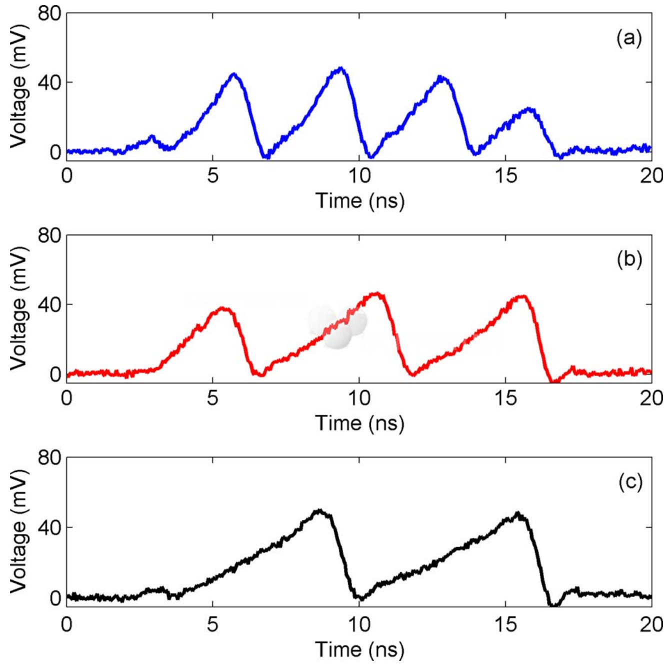

Fig. 6. Generated sawtooth waveforms with repetition rates of 280 MHz (a), 160 MHz (b) and 120 MHz (c).

The temporal frequency of the generated RF waveforms on a single pulse is determined by the SLM and the dispersive unit. By decreasing the spatial period of the modulation pattern and by utilizing lower dispersion DCMs ($\sim$17 times higher modulation rates can be obtained by using $-$40-ps/nm dispersive fiber as employed in [2]), waveforms with repetition rates $>$ 15 GHz can be achieved. On the other hand, the maximum RF bandwidth of the waveforms that can be acquired in the system is mainly limited by the diffractive optics and the detection system. Using diffraction gratings with more groove density larger than 600 lines/mm results in enhanced dispersion of the wavelengths over the entire DMD mirrors as well enables higher spectral resolution. Since the diffraction limits the resolution of the space-wavelength mapping ($\sim$100-μm spatial resolution is observed due to such system parameters of $\sim$0.87-mm beam waist and 200-mm lens (L1) focal length) on the DMD mirror array, reducing the focal size (with combination of larger beam and the Fourier lens with shorter focal length) as well yields significant improvement in final resolution down to the mirror pitch size, 10.8 μm. In addition, using LPF to eliminate the Fabry–Perot interference between the cover glass and the mirrors limits the maximum detectable frequency bandwidth to 1 GHz with $\sim$1-ns rise/fall time. Using a suitable cover glass, which is AR coated for NIR illumination, and high-speed detectors enables to catch the higher harmonics so that increases the temporal resolution, and hence, the smearing of the fine details of the arbitrary waveforms can be avoided.

3. Conclusion

We have introduced all-optical AWG by using DMD mirror array as SLM. By individually controlling the states of micromirrors, square and sawtooth waveforms at different frequencies are generated to demonstrate the concept. In the preliminary experimental work, we demonstrate 280-MHz sawtooth and 200-MHz square waveforms that are controlled by 1024 $\times$ 768 mirror arrays. We estimate that 1-GHz waveforms reconfigurable in $\sim$30 μs are also achievable by using the proposed approach. By compensating for the system nonidealities such as the nonuniformity of SC source and the system distortions through the patterns fed into the mirrors and by using an effective feedback algorithm, the system would converge to high-accuracy waveforms with minimum achievable error.

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