Optics Communications 338 (2015) 22–26

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A 2-GHz discrete-spectrum waveband-division microscopic imaging system

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ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form
1 September 2014
Accepted 4 September 2014
Available online 22 October 2014

Keywords:
Real-time imaging
Ultrafast
Discrete spectrum
Wavelength-to-space-to-time mapping
GHz imaging

ABSTRACT

Limited by dispersion-induced pulse overlap, the frame rate of serial time-encoded amplified microscopy is confined to the megahertz range. Replacing the ultra-short mode-locked pulse laser by a multi-wavelength source, based on waveband-division technique, a serial time stretch microscopic imaging system with a line scan rate of in the gigahertz range is proposed and experimentally demonstrated. In this study, we present a surface scanning imaging system with a record line scan rate of 2 GHz and 15 pixels. Using a rectangular spectrum and a sufficiently large wavelength spacing for waveband-division, the resulting 2D image is achieved with good quality. Such a superfast imaging system increases the single-shot temporal resolution towards the sub-nanosecond regime.

1. Introduction

Most of the current research in optical microscopic imaging aims to overcome the diffraction limit of spatial resolution; however, there are numerous applications that demand high temporal resolution (i.e., frame rate). The pursuit of high temporal resolution in an optical imaging system without sacrificing detection sensitivity is considerably restricted by the charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) imaging techniques [1], especially in those applications requiring temporal resolution of less than 1 μs, such as flow cytometry, microfluidics and surface detection [2–5]. In scientific research, an ultrafast single-shot diffraction imaging system using X-rays was proposed, but with the CCD acting as the detection device, which can only capture repetitive events [6]. In addition, a streak camera synchronized to a pulsed laser can be used to measure the time-of-flight of a light signal between the camera and the subject for each point of the image and further obtain 2D images [7]. However, this technique is only suitable for capturing an event that can be recreated exactly the same way multiple times. Recently, serial time-encoded amplified microscopy (STEAM) was demonstrated as a novel optical imaging technique that can achieve a high frame rate ($\sim$10 MHz) in real time [8–13]. STEAM is an optical method that uses a combination of spatially and temporally dispersive elements with a broadband mode-locked laser to achieve ultrafast single pixel imaging. An important feature of STEAM is the spectrum of the broadband laser source. The spectral characteristics of the mode-locked ultra-short pulse laser are not well controlled, including its spectral bandwidth and shape [14–18]. Moreover, limited by temporal dispersion, increasing the repetition rate of the broadband mode-locked pulse laser source is not available, which makes adjacent pulses overlap, e.g., an image of good quality cannot be obtained due to the small spectral bandwidth [19]. As a result, the frame rate of STEAM is confined to the Megahertz range, which impedes investigations of the phenomena in the sub-nanosecond time range. In photonic time stretching, a continuous-time large-bandwidth time-stretched signal is segmented and interleaved into multiple parallel channels using virtual time gating (VTG), which ensures via wavelength division multiplexing that no temporal overlap occurs for all of the channels [20,21].

In this paper, we propose a waveband-division imaging system based on a multi-wavelength source, which creates a record 2 GHz line scan rate. Unlike the mode-locked ultra-short pulse source, the advantage of waveband-division with a multi-wavelength source is that there is no loss for each discrete wavelength. Using wavelength division multiplexing, all of the wavelengths can be carved into two-channels to avoid pulse overlap induced by dispersion. Sufficient dispersion is a key element for wavelength-to-time mapping. Compared to the Gaussian shape of the mode-locked laser, the spectral shape of our multi-wavelength source

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http://dx.doi.org/10.1016/j.optcom.2014.09.077
0030-4018/

can be designed to be rectangular, which is beneficial to achieve a higher-quality image. Additionally, the wavelength spacing and the number of wavelengths can be appropriately chosen. With this novel method, we achieved a surface scanning imaging system at a record scan rate of 2 GHz with 15 discrete wavelengths. As far as we know, this is the first time that the temporal resolution of a real-time line scan imaging system reaches 500 ps based on the waveband-division technique.

2. Working principle

The principle of the proposed scheme is illustrated in Fig. 1. The complex electric field of a multi-wavelength source at each optical frequency ω_i can be described as follows [22]:

$$E_0(\omega_i, t) = \sqrt{S(\omega_i)}\exp\left[-j\phi_i(\omega_i)\right]\exp(-jw_i t), \tag{1}$$

where $S(\omega_i)$ is the energy density spectrum of the laser source and $\phi_i(\omega_i)$ is the frequency uncorrelated spectral phase. Multi-wavelength continuous waves (CW) sources are combined and feed into an amplitude modulator driven by a pulse train. A certain amplitude signal $m(t)$ is used for on-off control at all the wavelengths synchronously. The electric field after modulation can be expressed as follows:

$$E_1(\omega_i, t) = \sqrt{S(\omega_i)}\, m(t)\exp\left[-j\phi_i(\omega_i)\right]\exp(-jw_i t). \tag{2}$$

The modulated multi-wavelength pulses enter into the free space optical link. In this part, the information of the targets is mapped onto the discrete spectrum of each of the multi-wavelength pulses. This mapping is essentially a process of space-to-wavelength mapping. Next, the image-encoded pulses are broadened due to chromatic dispersion. As mentioned in Ref. [23] the final average time domain intensity waveform can be written as follows:

$$I_{out}(t) \propto \left[S\left(t/\ddot{\Phi}\right)R\left(t/\ddot{\Phi}\right)\right] \otimes |m(t)|^2, \tag{3}$$

where $R(\omega_i)$ is the reflective intensity from the samples corresponding to each frequency ω_i, $\mathrm{GVD}\equiv\ddot{\Phi} = -\partial^2\Phi/\partial\omega^2$ (Φ is the spectral phase transfer function of the dispersive medium along the entire optical bandwidth), $t \equiv \ddot{\Phi}\omega$, $\otimes$ denotes a convolution and the symbol $\propto$ denotes proportionality. According to Eq. (3), the average optical intensity can be simply calculated as the sum in intensity of the infinite set of field contributions corresponding to each optical frequency of the light source. In the particular case when $m(t)$ is short compared to the variations of the spectral density, one obtains [22]

$$I_{out}(t) \propto S\left(t/\ddot{\Phi}\right)R\left(t/\ddot{\Phi}\right)/\ddot{\Phi}, \tag{4}$$

Eq. (4) links the average temporal intensity of the waveform after gating and chromatic dispersion to the spectral density of the incoherent process via frequency-to-time mapping. In such an imaging system, the time parameters are determined by the following equations:

$$\Delta\tau \approx \Delta\lambda D T_0 = N\Delta\tau$$

where $\Delta\tau$ is the pulse width, $\Delta\lambda$ is the wavelength spacing of the multi-wavelength source, D is the dispersion value, N is the number of wavelengths and T_0 is the repetition period of the pulse train. In our scheme, the relationship between the time-stretched pulse duration T and the pulse train period T_0 complies with the following:

$$T_0 < T < 2T_0$$

This inequality indicates that the adjacent pulses after time stretching exhibit temporal overlap. This condition of the time-stretched pulse width being less than the pulse period is different than the condition of our previously reported paper [13]. Here, the time-domain overlapping part (encoded with the image) cannot be detected directly to recover the real image. Two filters are used to carve every image-encoded pulse into two different wavebands (as shown in Fig. 1). The number of wavelengths filtered from each channel is $N/2$. Next, the temporal width of the filtered pulse in each channel is less than T_0, which indicates that there is no temporal overlap in a single channel. Finally, the signal from both channels is detected using high-speed photodetector and is digitized using a high-speed oscilloscope.

3. Experimental setup and results

Fig. 2 shows the experimental setup. A distributed feedback (DFB) laser array is used as the optical source, which contains 15 discrete wavelengths. An array waveguide grating is used as a wavelength multiplexer to combine all of the CW laser beams. These beams are fed into an amplitude modulator driven by an

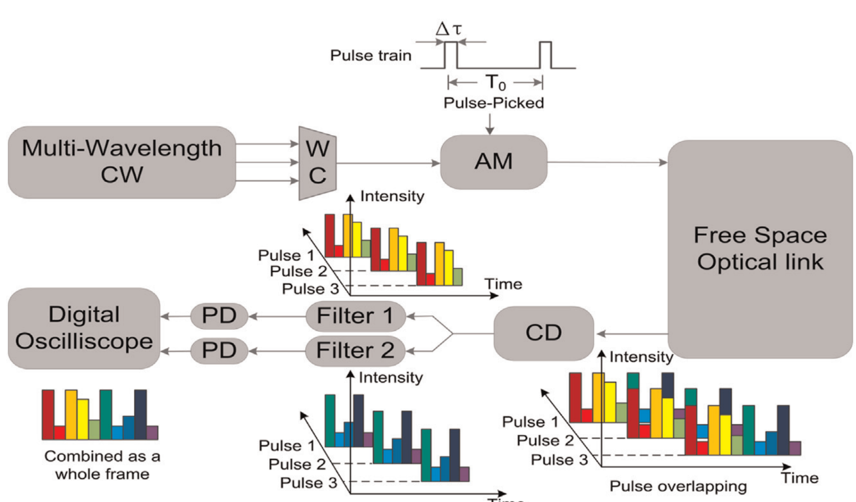

Fig. 1. Principle of wavelength division time-stretch imaging system with a line scan rate of gigahertz. CW: continuous wave, WC: wavelength combiner, AM: amplitude modulator, CD: chromatic dispersion, PD: photodetector.