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Optical time-stretch microscopy using few-mode fibers

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Abstract: We demonstrate a cost-effective and efficient approach for realizing ultrafast time-stretch microscopy in 1μm using the standard telecommunication single-mode fibers (e.g. SMF28 and dispersion compensation fiber (DCF)) as few-mode fibers (FMFs).

Dispersive Fourier transform (DFT), also known as time-stretch process, has been developed to deliver ultrafast real-time spectral measurement with a high spectral acquisition rate as high as >MHz – a speed not achievable with conventional spectrometers [1,2]. The same technique has also found applications in high-speed optical imaging, such as optical coherence tomography (OCT) [3] and serial-time encoded amplified microscopy (STEAM), or simply called *time-stretch microscopy* [4]. In the time-stretch process, an optical broadband pulse is stretched in time by group velocity dispersion (GVD) in a way that its spectral information is mapped into time. It thus facilitates ultrafast spectral measurements by using high-speed electronic digitizers. By far, the common time-stretch operation wavelength range is in the telecommunication band (~1550 nm) because of the wide availability of low-loss and dispersive single-mode fibers (SMFs) in this band – the central element for the time-stretch process [1,2,4-7]. Extending the utility of the time-stretch process to the favorable biomedical diagnostics window, i.e. ~1 μm, has in contrast been thought to be challenging because of the lack of the dispersive 1 μm specialty single-mode fibers (SMFs). We here demonstrate a cost-effective and efficient approach for realizing ultrafast time-stretched microscopy in the 1 μm window by using the standard telecommunication fibers (e.g. SMF28 and dispersion compensation fiber (DCF)) as the few-mode fibers (FMFs). Multi-mode fibers are generally avoided in the time-stretch process because the coexistence of modal dispersion and GVD leads to the ambiguity in the wavelength-time mapping. Nevertheless, instead of supporting excessive number of fiber modes, FMFs can be employed to achieve selective mode excitation more easily under the proper input coupling conditions. By evaluating the time-stretch process based on different FMFs, we show that SMF28 and DCF, having high dispersion-to-loss ratios, are the viable candidates for practical time-stretch-based spectroscopy and microscopy at 1 μm.

In time-stretch microscopy, the spatial coordinates of the specimen are first encoded in the wavelength spectrum of a broadband pulse with a "spectral shower" created by a spatial disperser, e.g. diffraction grating (DG). The pulse is then time-stretched by GVD so that the image-encoded spectrum is mapped into the serial temporal waveform which is finally captured by the electronic digitizer [4-7]. The broadband source in our setup is a supercontinuum (SC) (~900nm – 1300nm) generated by a 20-m long highly nonlinear fiber, which is pumped by a mode-locked-laser at the wavelength of 1064 with repetition of 20 MHz. A DG with a groove density of 1200 lines/mm and an objective lens (NA=0.66) are employed to focus the one-dimensional (1D) spectral shower onto the sample [5, 6]. The back-reflected spectral shower is collected by the fiber collimator (FC) and its spectrum is mapped into time domain by using different FMFs. Selective modal excitation in the FMF is done by introducing different lateral offsets between the facets of the input 1μm SMF and the FMF. In general, fundamental mode LP_{01} in the two FMFs (SMF28 and DCF) can be easily excited when there is no offset between the two fibers. In contrast, the higher-order LP_{11} mode in the SMF28 can be observed when an offset is introduced (Left inset in Fig.1). Finally, the time-stretched signal in the FMF is captured by a real-time oscilloscope (16 GHz, 80 GS/s). The complete 2D images are obtained by line-scanning either the sample or the 1D spectral shower in the orthogonal direction. This line-scan operation is particular useful for high-speed flow cell imaging applications [7]. The mode profiles at the output fiber facets were also imaged using a near-infrared camera (Fig. 1(b))

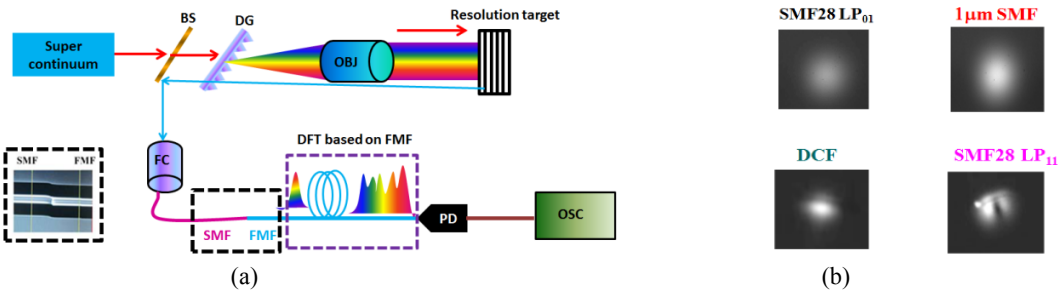

Fig 1 (a) Experimental set up of time-stretch microscopy at 1μm using FMF. Left bottom inset: an image of the fused fiber. The offset between the two fibers can be observed at the connecting facets. (b) Captured mode profiles of different fiber modes.

In this setup, the same time-stretched technique can also be used for detailed characterization of the GVD curves among different fiber modes in the FMFs (Fig. 2(a)). It is done by evaluating the wavelength-time mapping of a tunable bandpassed-SC (bandwidth of~ 8 nm) across 1050 nm – 1140 nm. We note that as the spectral resolution in the time-stretch process, and hence the spatial resolution in time-stretch imaging, scales with GVD [2,6], large GVD is thus always essential for achieving high-resolution time-stretch microscopy. Equally important is the intrinsic dispersive fiber loss which degrades the signal-to-noise ratio, and thus the detection sensitivity. In this regard, a metric which can reflect the trade-off between the GVD and loss should be used to define the *effectiveness* of the time-stretch process, i.e. GVD-to-loss ratio R (in ps/nm-dB). From Fig. 2(a), both the LP_{01} modes of the SMF28 and the 1 µm SMF have the comparable R-ratios of ~50 ps/nm-dB – showing the similar GVD per unit of loss. By selectively exciting the higher-order LP_{11} mode in SMF28, we can achieve much higher GVD (~100 ps/nm·km), it however comes at the expense of a significant fiber loss (~17dB/km), resulting in an R-ratio of only 3-6 ps/nm-dB. Surprisingly, we observed that the R-ratio of the LP_{01} mode in the DCF is as high as ~150 ps/nm-dB – showing a favorably large dispersion with low loss at 1µm for practical FMF-based time-stretch microscopy.

We performed time-stretch microscopy to image a resolution target (USAF-1951) based on different fiber modes in the FMFs and the 1µm SMF (Fig. 2(b)-(e)). Similar to the time-stretch image using the 1µm SMF (Fig. 3(b)), the images based on LP_{01} modes in the SMF28 and DCF resolve well the smallest line feature (a linewidth of ~2 µm in Group 7) (Fig. 2(c)-(d)). Note that the single-shot line scan (along the x-direction) is obtained only within few ns, determined by the GVD of the fiber and the source bandwidth [2]. It thus clearly shows the feasibility of employing FMF as a cost-effective option for high-speed time-stretch microscopy. For time-stretch imaging based on the LP_{11} mode in SMF28 (Fig. 3(e)), the excessive loss prohibits higher total GVD using a longer fiber (limited at ~35 ps/nm with a length of 0.35km). Hence, it is only able to resolve the features with a minimum linewidth of 15µm (Group 6). In addition, the "ghosting effect" appeared in the image can be attributed to the mode coupling in the SMF28, which is verified by the interference pattern in the background (Fig. 3(e)). We note that the intrinsic dispersive loss can be circumvented by optically amplifying the time-stretched signal either using distributed Raman amplification in the same fiber [1,2,4-7] or the discrete optical amplifiers, which are commonly available in the 1 µm range (e.g. YDFA, and semiconductor optical amplifiers).

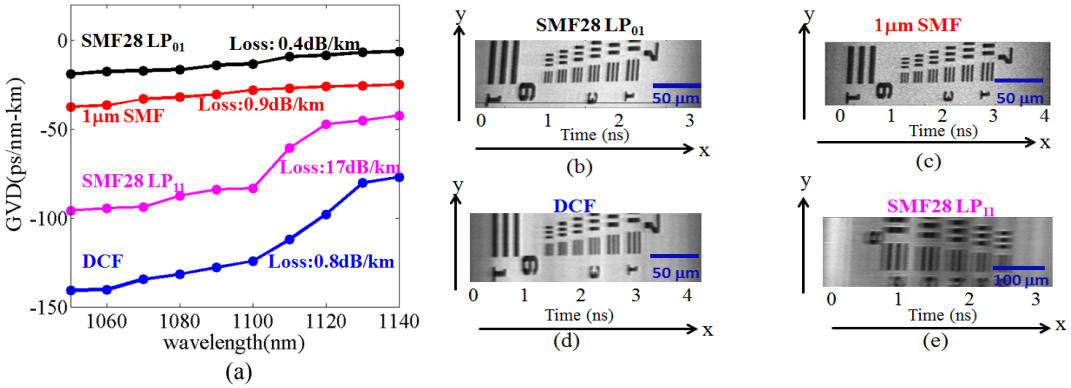

Fig.2 (a) Measured dispersion curves of different fiber modes in the FMF and 1µm SMF. (b-e) Images captured by time-stretch microscopy using different fiber modes: (b) LP_{01} mode in a 9km-long SMF28, (c) LP_{01} mode in a 5 km-long 1µm SMF, (d) LP_{01} mode in a 1.44km-long DCF, and (e) LP_{11} mode in a 0.35km-long SMF 28.

In summary, we report time-stretch microscopy in the 1-µm range, a favorable window for biomedical diagnostics, by using the standard telecommunication SMFs (SMF28 and DCF) as the FMFs instead of the high-cost specialty 1-µm SMF. Albeit the complication introduced by the mode coupling, higher-order mode in the FMFs can also be exploited for time-stretch-based measurements if one can identify the proper fiber length at which minimal mode coupling would occur. It should be emphasized that the intrinsic dispersive fiber in all above cases can be readily circumvented by optical amplification in the time-stretch process – realizing high-speed and high-sensitivity spectroscopy and microscopy for many high-throughput diagnostic applications, e.g. imaging flow-cytometry.

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