Title	Dispersive fourier transform at 1 μm based on high-order modes in few-mode-fiber
Author(s)	Qiu, Y; Xu, J; Wong, KKY; Tsia, KK
Citation	The 2012 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA., 6-11 May 2012. In CLEO Proceedings, 2012, p. 1-2, paper no. JTh2A.8
Issued Date	2012
URL	http://hdl.handle.net/10722/160273
Rights	Conference on Lasers and Electro-Optics Proceedings. Copyright © IEEE.

Dispersive Fourier Transform at 1 μm based on High-Order Modes in Few-Mode-Fiber

Yi Qiu, Jingjiang Xu, Kenneth K. Y. Wong, Kevin K. Tsia*

Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong.
**Email: tsia@hku.hk*

Abstract: We report that high-speed and real-time spectral acquisition is achieved by dispersive Fourier transform (DFT) in the 1-μm spectral window using the selectively-excited higher-order modes in the few-mode fibers (FMFs).

OCIS codes: (260.2030) Dispersion; (300.6530) Spectroscopy, ultrafast; (300.6360) Spectroscopy, laser

Optical spectroscopy represents one of the most ubiquitous optical diagnostics tools in numerous biomedical applications.[1] It has been well-recognized that real-time and high-speed spectroscopy can help improving both the diagnostic efficacy and efficiency by providing fast dynamical information, or delivering high-throughput and high-content screening. However, it has been a challenging task as conventional spectrometers generally lack the speed to meet the aforesaid criteria. Wavelength-time spectroscopy, called dispersive Fourier transform (DFT), has been demonstrated to perform ultrafast real-time spectroscopy with spectral acquisition rate of >MHz, a speed not achievable with conventional spectrometers. In this approach, the spectral information of an optical broadband pulse is mapped into time using group velocity dispersion (GVD). Its time-domain operation uses a single photodetector and a high-speed electronic digitizer to acquire spectra in real time. Most of the prior works on DFT-based spectroscopy operate mainly in the telecommunication wavelength band (i.e. ~1500 nm) primarily due to the fact that low-loss highly-dispersive fibers (e.g. dispersion compensation fibers) are widely accessible for long-haul telecommunication. As far as biophotonic applications concern, it would be more appealing if one can operate DFT at ~1-μm range – a favorable spectral window for biomedical diagnostics. However, low-cost single-mode fibers (SMFs) and high-performance dispersion-engineered fibers are not readily available for DFT at these wavelengths – hampering the utility of DFT in real practice.

We here demonstrate a cost-effective and efficient approach for realizing DFT at 1 μm by using the low-cost standard telecommunication SMFs (e.g. SMF28) as few-mode fibers (FMFs). They are regarded as FMFs in the 1μm range because the cutoff wavelength of these fibers is typically at ~1200 nm. In contrast to multi-mode fibers (MMFs) which allow hundreds of propagation modes, FMFs support only a few modes. Generally, multi-mode guiding is not recommended for performing DFT because that the modal dispersion, which occurs simultaneously with GVD, introduces the ambiguity in the wavelength-to-time mapping during DFT. Nevertheless, by proper control of the input-coupling conditions, we experimentally demonstrate that selective mode coupling can be robustly achieved and a clear wavelength-to-time mapping in DFT can be achieved not only for the fundamental mode (LP_{01}) but also the higher-order mode (LP_{11}). Intriguingly, the higher-order modes (e.g. LP_{11}) can be exploited for performing DFT because they exhibit order-of-magnitude enhancement in GVD – a prerequisite of achieving high spectral resolution in DFT. In our experiments, we observed the LP_{11} shows 25-fold increase in GVD compared to the LP_{01}. While the large GVD inevitably comes with high optical loss, it is not the inherent limitation of this FMF-based DFT as broadband optical amplification (such as Raman amplification) can be performed simultaneously with DFT at the 1-μm range. Such optical amplification scheme greatly enhances the detection sensitivity without compromising the speed, named as amplified DFT (ADFT) [1,2].

We employed a mode-locked laser at a center wavelength of 1064nm with a repetition rate of 20MHz to pump a 20-m highly nonlinear fiber to generate a supercontinuum (SC) spanning from ~800 nm to ~1300 nm. SMF 28 was used as the FMF in the 1-μm range for performing DFT which maps the spectral information of the SC pulse into

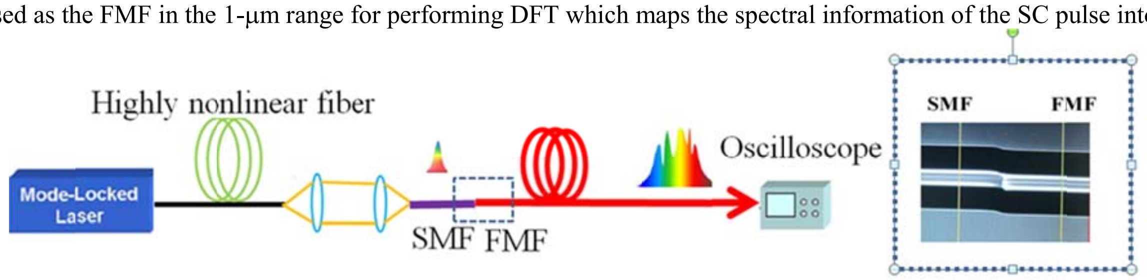
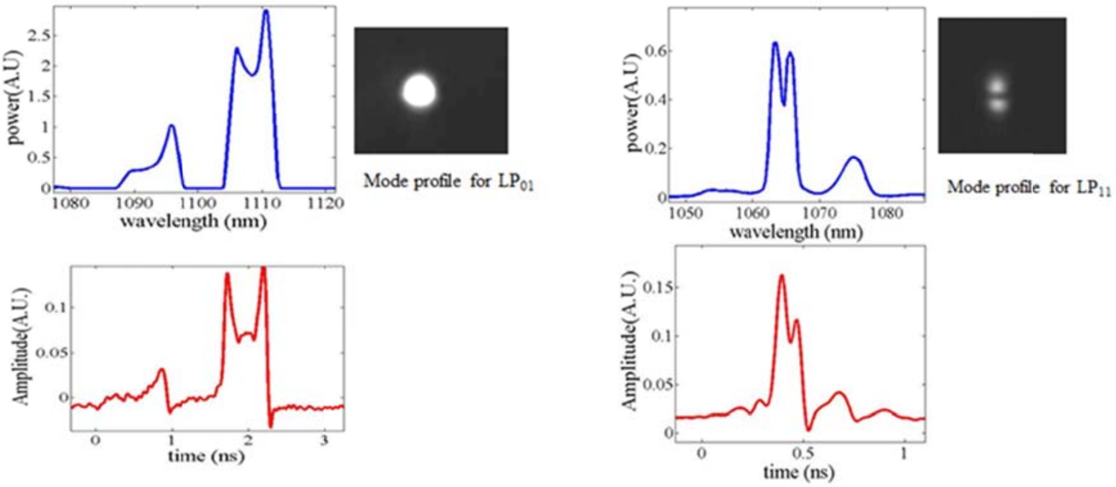


Fig 1 Experimental set up for dispersive Fourier transform (DFT) at 1μm using FMF. Right inset: the image of the fused fiber. The offset between the two fibers can be observed at the connecting facet.

the time domain. A real time oscilloscope (16GHz, 80GS/s) is used to capture the signal (Fig. 1). We connected the FMF and the SMF (single mode for 1-μm range, 1060-HI) together by fusion splicing. In order to selectively excite the higher-order modes, the cleaved facets of the FMF and the SMF were laterally offset (inset of Fig. 1). Different amounts of the offset (both in the orthogonal directions on the transvers plane) can be precisely controlled by the fusion splicer in order to facilitate different high-order-mode coupling conditions.

Fig. 2 shows the comparison of the FMF-based DFT operations between using the fundamental mode LP_{01} and the first higher-order mode LP_{11}. The mode profiles imaged at the end facet of the FMFs by an infrared camera are also shown as the insets in the figure. It is clear that the wavelength-time mapping can be realized by the selectively-excited $\mathbf{LP_{01}}$ and $\mathbf{LP_{11}}$ modes in the FMFs with the nanosecond time-scale. From the figures, we estimated the dispersion of the LP_{11} mode to be as high as 80 ps/nm·km which is almost 25 times higher than the dispersion of LP_{11} mode, which is ~3ps/ nm·km. We note that this value is also larger than the dispersion of the 1-μm SMF (~10ps/nm·km). We note that a more accurate evaluation of the GVD profile (as a function a wavelength) can be performed based on optical low coherence reflectometry [3]. In the DFT process, the loss for LP_{01} mode and LP_{11} mode were measured as 5dB/km and 17 dB/km, respectively. This inherent dispersive loss can be readily compensated by simultaneous optical amplification within the fibers. High-gain and wideband optical amplification in the 1-μm range can be achieved by fiber Raman amplification, fiber optical parametric amplification [3,4]. Off-the-shelf Ytterbium-doped fiber amplifiers (YDFAs) and 1-μm semiconductor optical amplifiers (SOAs) can also be utilized to serve as the additional amplification mechanisms to enhance the detection sensitivity of the FMF-based ADFT.



(a) (b)

Fig.2 Wavelength-time mapping of (a) LP_{01} mode with a 42 km FMF and (b) LP_{11} mode with a 400-m FMF. The upper blue plots: the input SC spectra. The lower red plots: The temporal waveform after the DFT process. Insets: (left) Mode profile of LP_{01}. (right) Mode profile of LP_{11}.

In summary, we report a cost-effective approach for realizing DFT-based spectroscopy at the 1-μm range by using the standard telecommunication SMF as a FMF instead of high-cost specialty 1-μm SMF. By an in-house fusion-splicing technique, we can selectively excite the fundamental mode LP_{10} and the higher-order mode LP_{11} in the FMF fiber, both of which can exhibit a clear wavelength-time mapping even without additional amplification. Intriguingly, the dispersion of the LP_{11} mode shows ~25-fold enhancement compared to that of the LP_{01}. Harnessing the readily-available high-performance and low-cost telecommunication fibers, this FMF-based DFT approach represents a cost-effective approach to realize high-speed DFT-based spectroscopy particularly in the biomedical diagnostics spectral window. The detection sensitivity can be efficiently boosted up when optical amplification is incorporated, i.e. FMF-based ADFT.

References

[1] D. R. Solli, J. Chou and B. Jalali, Nature Photonics 2, 48 - 51 (2008)
[2] Goda, K , Solli,DR , Tsia, KK , Jalali, B, PRA 80,043821 (2009)
[3] Sven Ring, David Menashe, Uri Levy, Serge Steinblatt, Yochay Danziger1 and Moshe Tur , OFC/NFOEC 2008
[4] J. E. Sharping, M. A. Foster, A. L. Gaeta, J. Lasri, O. Lyngnes, and K. Voge , Opt. Express 15, 1474 (2007).
[5] J. Fan, A. Dogariu, and L. J. Wang, Appl. Phys. B 81, 801 (2005).