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Tunable four-wave mixing based light source for nonlinear imaging applications

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1. Abstract

We present a widely tunable all-fiber optical parametric oscillator (FOPO) system driven by the nonlinear effect of Degenerate Four-Wave Mixing (D-FWM). We introduce a novel all-fiber method for wavelength tuning over more than 40 nm in normal dispersion regime, based on self-phase modulation (SPM) induced spectral broadening. The FOPO source emerges as a pivotal technology for advancing biomedical diagnosis particularly enabling in vitro chemosensitivity measurements.

2. Introduction

Label-free imaging based on Raman microscopy offers several significant advantages including non-invasive imaging construction, no need for sample preparation, high spatial resolution, and high chemical selectivity. Among these techniques, stimulated Raman scattering (SRS) provides a stronger signal and thus faster imaging speed compared to spontaneous Raman microscopy [1]. Currently, available SRS light sources allow for measurements in the C-H stretch regions by exploiting, for instance, second harmonic generation (SHG) in nonlinear crystals and supercontinuum generation (SCG) in highly nonlinear fibers, which often require free-space components in their design [2]. A tunable light source based on SPM of chirped pulses at 1030 nm, compressed to femtosecond regime by a free-space grating compressor, has been proposed for SRS imaging in the fingerprint Raman region [3].

To cover both the entire fingerprint and C-H stretch regions, a tunable FOPO source has recently been demonstrated. This source uses FWM generated in photonic crystal fiber (PCF) placed in a resonant cavity, pumped by a wavelength-tunable oscillator mode-locked by a semiconductor saturable absorber mirror (SESAM) [4]. However, semiconductor materials degrade over time due to prolonged exposure to high-intensity laser pulses, necessitating periodic replacement.

An alternative method for achieving a widely tunable pump for FOPO has been presented in [5,6], based on filtered SPM-induced spectral broadening followed by pulse amplification. However, this system is bulky and complex, involving several free-space optical components, such as for instance grating compressor and galvanometric scanner in 4f configuration. In our work, we implement a similar concept but in all-fiber configuration, instead.

3. Experimental results

Figure 1 presents the scheme of our FOPO light source. The resonant cavity is pumped by a high-power laser system based on an Ytterbium-doped fiber (YDF) oscillator mode-locked by the Nonlinear Optical Loop Mirror (NOLM) technique, which ensures environmentally stable and long-term reliable operation [7]. It provides chirped pulses of 10 ps at a repetition rate of 15.9 MHz and at a fixed central wavelength of 1030 nm. To achieve a wide tunability range of the pump, we utilized SPM spectral broadening. Efficient SPM generation requires pulses with a temporal duration below 1 ps typically necessitating the use of a free-space grating compressor in normal dispersion regime. Different from conventional methods, we pre-compressed the chirped pulses by implementing a narrow-band fiberized spectral filter. This approach allowed us to shorten the pulse duration from 10 ps to below 1 ps, that was sufficient to generate SPM spanning over a broad 85 nm range. The all-fiber configuration enhances the system stability while significantly reducing the complexity of the set-up.

Next, we employed a double-filtering with 1 nm-tunable filter followed by an appropriate amplification system. As a result, we obtained a pump beam tunable from 1025 nm up to 1063 nm, with 1-nm spectral bandwidth and up to 2 W average power. This pump allows for spectral tunability of the D-FWM signal from 730 nm to 950 nm with an average output power of 35 mW, as illustrated in Figure 1b. Considering the second beam at around 1030 nm, this range enables measurements in the fingerprint and C-H stretch regions from 929 cm^{-1} to 3942 cm^{-1}. Our system has potential applications in biomedicine, particularly when integrated into a SRS microscope, advancing label-free nonlinear imaging technologies.

4. Funding

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5. References

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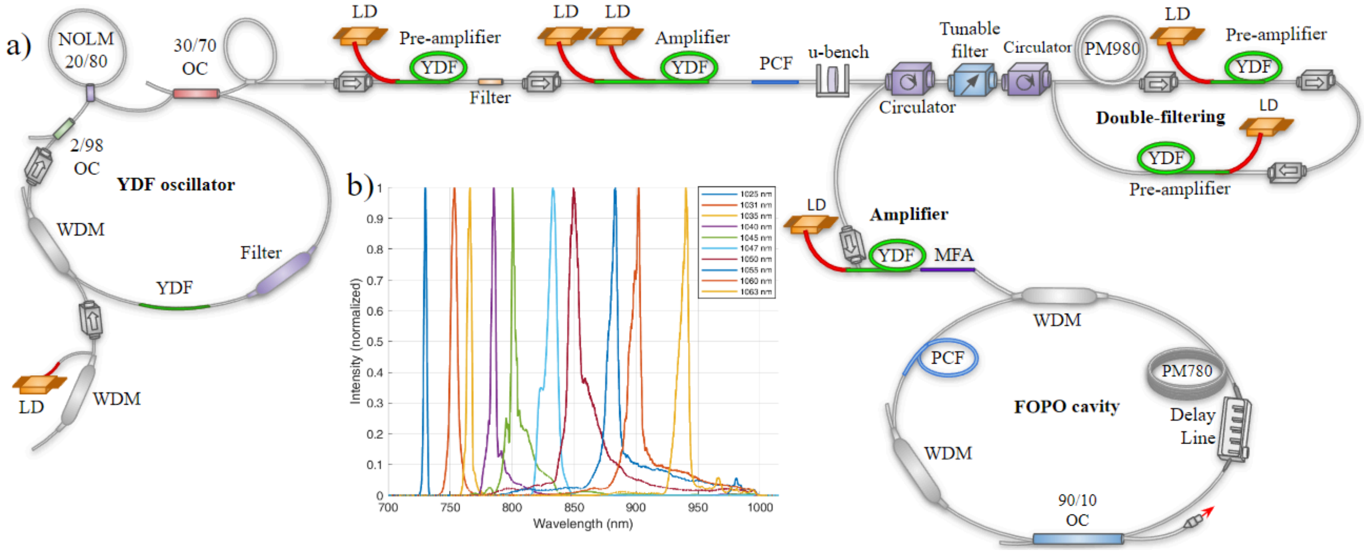

Figure 1. a) Experimental set-up of the D-FWM light source in the FOPO configuration. **b)** Tunable D-FWM signal spectra.