All-fiber sources for visible femtosecond pulses using resonant dispersive waves

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Fully fiber-integrated femtosecond laser systems covering the visible spectrum could take advanced biomedical imaging techniques from the laboratory to real-world applications.

Biomedical imaging for research and diagnostics increasingly requires the use of advanced optical imaging techniques. Imaging modalities include single- or multiphoton fluorescence spectroscopy, optical coherence tomography, and various kinds of Raman spectroscopies. These methods require the use of advanced laser sources that feature moderate- to high-power pulses of picosecond or femtosecond duration, and which span a broad range of the visible and/or near-IR spectrum. Present-day laser systems that meet these criteria are typically bulky and sensitive, and require specialist operators and regular maintenance. The development of laser sources that are sufficiently robust and compact for operation by non-specialized staff in a clinical environment would make it possible to use these advanced optical imaging techniques for direct point-of-care analysis of biosamples, or even live patients. An example is diagnostics for skin cancer.

Lasers are by nature restricted to emit light at frequencies that correspond to the optical transitions of the gain material. To broaden the laser wavelength range, we must resort to non-linear optical wavelength conversion. For femtosecond operation, typical present-day systems use titanium-sapphire lasers that are subject to frequency conversion by optical parametric oscillators. These devices are based on free-space optical components, and are therefore highly sensitive to alignment and temperature fluctuations. A more robust alternative is ytterbium (Yb)-doped fiber lasers, which are highly stable due to the tight confinement of light in the fiber core. Furthermore, it is possible to splice all the Yb-doped fibers together to form a monolithic optical system. The challenge is then to sustain and control high-power ultrafast pulses in the fibers, and to perform the required spectral conversions efficiently. A promising approach to meet this challenge uses the concept of ‘Cherenkov’ radiation (CR) in optical fibers.\(^1,2\) A specially designed fiber, which features optical non-linearities and dispersion properties, enables a femtosecond pump pulse propagating in the fiber to undergo a runaway compression and collapse. For a brief instant, the collapse leads to an extreme spectral broadening of the pulse, and some of the optical power is permanently deposited at one or

Continued on next page
more ‘resonant’ wavelengths, which are also determined by the fiber dispersion. Fiber-based CR enables wavelength conversion from near-IR wavelengths into the entire visible range.\(^3\) In addition, by suitable design of the laser system it is possible to obtain high conversion efficiencies,\(^4\) ultrafast CR pulses, low noise, and smooth, well-defined CR spectra.

We have realized a fully fiber-spliced CR source that uses advanced photonic crystal fibers (PCFs)\(^5\)–\(^7\) (see Figure 1). PCF technology enables dispersive compression of high-power pulses to femtosecond durations in hollow-core optical fibers with ultralow non-linear coefficients. The technology also allows for the design of highly non-linear small-core fibers with the dispersion properties that are required for conversion of \(\sim 1\mu m\) pump pulses into CR across the visible spectrum. In our setup, a low-power fiber oscillator produces \(\sim 230\) fs output pulses, which are dispersively stretched and amplified in standard fibers. Compression is achieved in a hollow-core photonic-bandgap fiber, which provides stable single-mode output and useful polarization maintenance. All these fibers are spliced together with losses of below 1dB/splice. The final coupling from the hollow-core fiber to the highly non-linear PCF may be free-space for laboratory experiments, or fiber-spliced using intermediate fibers with \(\sim 4dB\) loss.\(^8\)

With our setup, we generated CR pulses of up to \(\sim 170\) pJ at a wavelength tunable from 580 to 630nm by varying the input pump power\(^8\) (see Figure 2). We recorded noise measurements and, from these, a signal-to-noise ratio of between 20 and 40 at CR pulse energies of above 100pJ, which is an order of magnitude better than that of commercial fiber-based supercontinuum sources.\(^9\) The CR pulses showed smooth autocorrelation spectra, which had an estimated temporal width of \(\sim 100\) fs. These specifications are sufficient for practical imaging applications.\(^2\)

To improve our technology we would increase the tunability of the output wavelength to cover the visible spectrum. The CR wavelength depends on the PCF core diameter, and can therefore be shifted by varying the fiber properties. We have investigated CR generation in non-linear fiber links that feature sections of PCF with different core diameters. As shown in Figure 3, such a setup makes it possible to switch the CR between blue and yellow-red wavelengths by varying the input polarization relative to the principal axes of the weakly birefringent PCF.\(^10\),\(^11\) Complex non-linear polarization dynamics in the initial pulse compression process cause the CR to be generated in different portions of the fiber, depending on the input polarization state. So far, we have realized this polarization-control technique only with free-space coupling to the non-linear PCF. However, we are currently investigating ways to enable wide tunability of the CR wavelength, even in a fully fiber-spliced system.

In summary, we have developed a fully fiber-spliced CR source that uses advanced PCFs to enable practical imaging applications. Our current and future research focuses on increasing the source’s wavelength flexibility.

\(\text{Figure 2. CR spectra of a highly non-linear PCF pumped by the monolithic fiber laser system.}\)

\(\text{Figure 3. Contour plot of spectral dependence on pump polarization in a PCF that contains sections of different core diameters. A.U.: Arbitrary units.}\)

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References