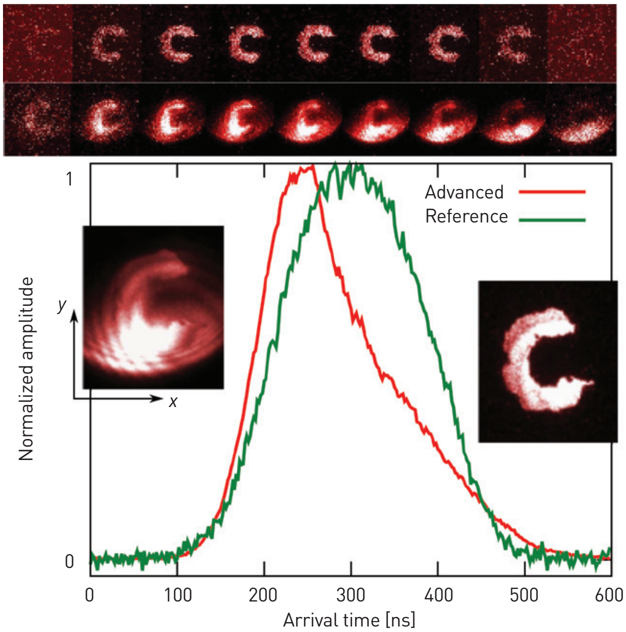
ULTRAFAST OPTICS

Fast Light and Superluminal Images via Four-Wave Mixing

Manipulating the group velocity of light has resulted in many advances, including slowing light to a car's pace, stopping light and even forcing pulses to propagate faster than the speed of light in a vacuum.[1] While the group velocity is equal to or less than the speed of light in a vacuum (*c*) when propagating through a medium exhibiting normal dispersion, anomalous dispersion allows the group velocity to be greater than *c*, or even negative.[2] Strangely, the peak of a pulse propagating with a negative group velocity through a medium appears to exit the medium before entering it. This is a result of interference from spectral components of a pulse propagating with different phase velocities in the medium.

We have shown that the nonlinear process known as four-wave mixing can be used to generate pulses that propagate with a large negative group velocity and can also support fast light images.[3,4] We pumped a cell containing hot rubidium vapor with a strong laser beam detuned slightly away from an atomic resonance. Next, we injected a probe beam at a small angle relative to the pump beam. Two pump photons are essentially converted into one photon in the probe mode and one conjugate photon, where the latter propagates on the opposite side of the pump relative to the probe.

This process results in narrow, asymmetric gain lines near the frequencies of the probe and the conjugate. A gain feature exhibits normal and anomalous dispersion at the center and wings of the gain line, respectively. By tuning the probe beam to the region of anomalous dispersion, we achieved record relative pulse advancements of greater than 60 percent. We also demonstrated that the conjugate pulses generated by the four-wave mixing interaction can be tuned to propagate with negative group velocities.



The letter "c" propagating with a negative group velocity.[4] Green and red curves are the reference and advanced normalized pulse amplitudes of the entire image, respectively. The advanced image's peak arrives about 50 ns earlier than the pulse propagating at the speed of light in vacuum.

The process generates fast light but does not require a cavity and can therefore support multiple spatial modes. An image can be imprinted on the probe beam and propagate with a negative group velocity through the atomic vapor. All parts of the image propagate superluminally. There is a tradeoff between image quality, pulse distortion and relative pulse advancement. There are tools to change the relative pulse advancement, however, such as changing the pump and probe powers and relative detunings.

Our process has generated nonclassical states of light because the probe and conjugate photons are created in pairs.[5] We are investigating the effect of anomalous dispersion on these quantum correlations. OPN

Researchers

Ryan T. Glasser (ryan.glasser@gmail.com), **Ulrich Vogl** and **Paul D. Lett**
National Institute of Standards and Technology and the University of Maryland, Md., U.S.A.

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ULTRAFAST OPTICS

Towards Ultrafast Integrated **Optical Clocks**

Future photonic materials and optical integration strategies will likely be compatible with current CMOS fabrication technologies and platforms.[1,2] We demonstrated that it is possible to obtain mode-locked soliton pulse emission in a fiber loop laser by combining the nonlinear element with the high-finesse filter, exploiting a novel interaction mechanism that we termed filter-driven four wave mixing (FD-FWM).[3]

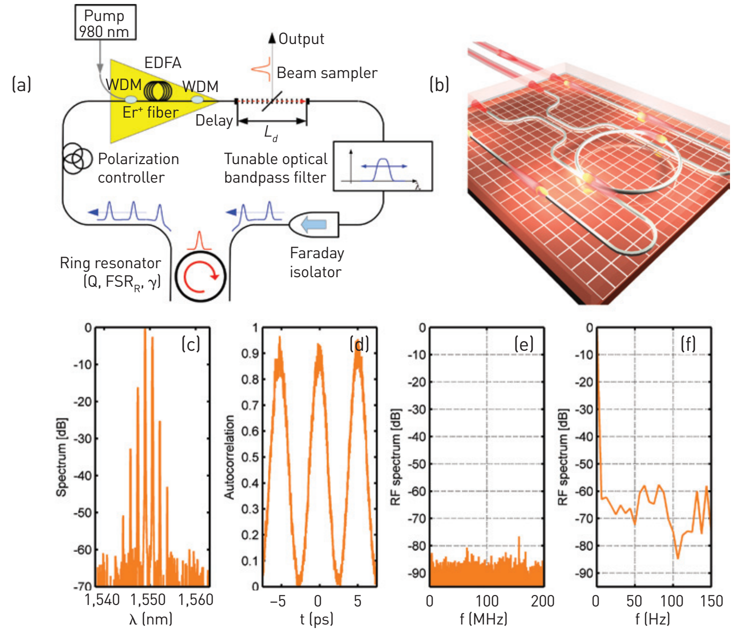
Future time-domain–multiplexed optical networks will be synchronized with the aid of optical clocks. These clocks will provide highly synchronized pulse trains exceeding hundreds of GHz repetition rates. Exploiting passively mode-locked lasers is the key approach to generating these pulse trains. They are composed of a band-limited amplifier, a dispersive element and a nonlinear element. However, high repetition rates require short laser cavities with extremely high gain per unit length. In addition, the comparatively low finesse of the cavity results in a large Schawlow-Townes phase noise limit.

In an alternative approach, a high-finesse resonant filter is embedded in a long nonlinear laser cavity. The laser emits soliton pulses with a repetition rate equal to the filter-free spectral range, in a configuration known as dissipative four-wave mixing (DFWM).[4]

The filter selects modes that exchange energy via FWM and locks their mutual phase, enabling traveling soliton pulses to form. While this is appealing for extremely high repetition rates, this design usually exhibits supermode instabilities and significant output amplitude noise.[5] Hence, DFWM lasers have had little practical impact so far.

As the efficiency of the nonlinear interaction is boosted by the internal resonator field-enhancement, our FD-FWM scheme eliminates the need of long cavities to provide the necessary large gain and Kerr nonlinearity. When one main cavity mode oscillates per filter resonance, nonlinear mode locking leads to a stable pulsed emission at a 200-GHz repetition rate with an electrical noise bandwidth estimated to be lower than 6 Hz at -60 dB, a measurement-limited value. In addition, we estimated the output spectral combs to have linewidths much less than 130 KHz, limited only by acoustic environmental noise.

Our results indicate that the intrinsic Lorentzian contribution to the linewidth is actually much less than 13 kHz, remarkably low for a 200-GHz laser and, if correct, implies that this laser architecture has enormous potential for extremely precise, high-repetition-rate pulse generation for many ultra-high-speed applications. OPN



(a) Sketch of the laser configuration. The free space delay line was used to adjust the spectral position of the main cavity modes relative to the ring resonances. (b) The ring resonator microcavity on the photonic chip. (c) Spectrum and (d) autocorrelation of the laser output. (e) Radio-frequency spectrum of the output laser amplitude. (f) Detail of the radio frequency spectrum profile around the DC component.

Researchers

Alessia Pasquazi and **Roberto Morandotti**
INRS-EMT, Québec, Canada

Marco Peccianti
(m.peccianti@gmail.com)
National Research Council, Rome, Italy

Brent E. Little, *Infinera Ltd., Sunnyvale, Calif., U.S.A.*

Sai T. Chu, *City University of Hong Kong, China*

David Moss, *University of Sydney, Australia*

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ULTRAFAST OPTICS

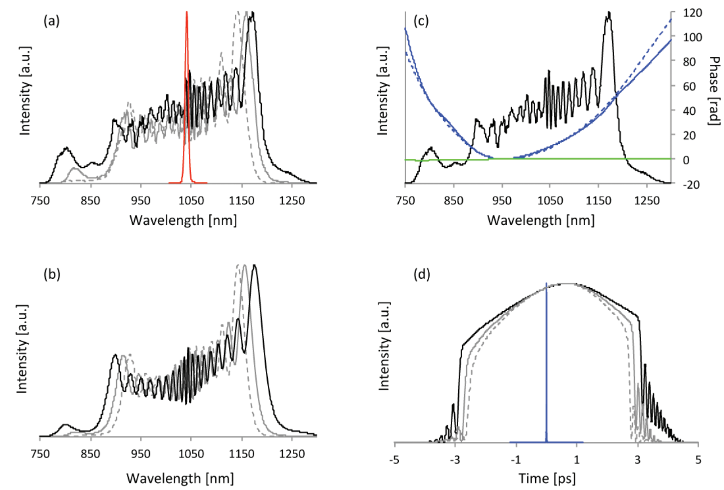
Wave-Breaking Extended Coherent Fiber **Supercontinuum Pulse Compression**

Like surface water wave breaking, optical wave breaking (WB) is a phenomenon that occurs when an optical pulse propagates in a normally dispersive nonlinear fiber.[1,2] It is often avoided in fiber continuum compression experiments by using lower coupling power or shorter fiber length, because the WB-extended continuum has higher-order spectral phase distortions that cannot be compensated by a quadratic compressor, a prism pair or a grating pair. This issue can be resolved when an ideal compressor such as a 4f pulse shaper is used. Linear and nonlinear chirps can be removed by arbitrary phase shaping toward transform-limited pulse compression.

In our experiment, the onset of a spectral tail at lower coupling power and the development of the tail into sidelobes at higher coupling power at both ends of the spectrum suggest the occurrence of WB.[3] With the WB-extended spectrum at the highest power, we compressed the supercontinuum to a pulse width of 6.4 fs using a 4f pulse shaper. We achieved the pulse measurement and compression by performing a multiphoton intrapulse interference phase scan.[3,4]

Our work included the theoretical modeling of the pulse progression by the scalar generalized nonlinear Schrödinger equation. The simulated spectra at different powers reproduced the fringe-like spectra and the evolution of WB. In the time domain, the trailing edge experienced self-steepening, creating an optical shock followed by temporal oscillations from the interference of the generated high-frequency (short-wavelength) components and unshifted light. At elevated power, the oscillations strengthened as the spectral tail developed into a side lobe, and the oscillations at the leading edge were simultaneously initiated. Also, the predicted spectral phase resembled the measured one except for the spectral ranges where the intensity of the supercontinuum is low. The agreement between simulations and experiments confirms the occurrence of WB and explains its non-symmetric development at both ends of the spectrum.

The combination of the WB-extended supercontinuum and arbitrary phase compensation allows us to generate 0.1 W, 80 MHz, near-transform-limited 6.4-fs (FWHM) pulses at a high compression ratio (28×). A broader bandwidth and higher compression ratio could be attained by overcoming nonlinear depolarization at higher coupling power or longer fiber length. The ultrabroad bandwidth and high coherence of the fiber light source could be appealing to nonlinear optical microscopy and spectroscopy using coherent control methods, especially for nonlinear interferometric vibrational imaging and other types of interferometric coherent anti-Stokes Raman scattering imaging.[5] OPN



(a-b) Experimental and theoretical supercontinuum spectra at three coupling powers. (dashed gray: 0.17W; gray: 0.21W; black: 0.27W). WB emergence is seen at both ends. The red spectrum in (a) is the pump laser spectrum. (c) The WB-extended supercontinuum spectrum (black), spectral phase predicted by the S-GNLSE (dashed blue), measured by MIIPS (blue), and residual phase after compression (green). (d) Temporal profiles of the pulses corresponding to three coupling powers in (a) and (b). The blue profile is of the pulses compressed from the WB extended supercontinuum.

Researchers

Yuan Liu, **Haohua Tu** and **Stephen A. Boppart** (boppart@illinois.edu)
University of Illinois at Urbana-Champaign, U.S.A.

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