tuning the pump wavelength changes the co-propagating signal wavelength, whereas the counterpropagating idler's wavelength remains unchanged. Second, the linewidth of the idler waves was two orders of magnitude narrower than that of either signal or pump. These unique properties open up possibilities for broadband pulse generation in the near-infrared or mid-infrared regions, and for tuning a narrowband mid-infrared idler wave with high precision.

The demonstration also opens the door for the development of many other nonlinear optical devices with increased functionality, for instance, tunable mirrorless nonlinear resonators, in which the stability and coherent properties of the oscillating waves will be even further improved. The fact that the OPO can be made robust and compact also lends itself to potential uses in on-site field work.

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OPTICAL METROLOGY

Everything under control

High-fidelity line-by-line spectral shaping has been applied to more than 100 phase-stable optical frequency-comb components. This represents a significant step towards optical arbitrary waveform generation and control.

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The development of radiofrequency oscilloscopes and waveform generators in the first half of the twentieth century laid the foundation for today's electronics industry. Scientists and engineers now stand on the brink of developing an ultrabroadband (more than 100 THz) optical arbitrary waveform generator (OAWG). Such a device would give us more than a thousandfold improvement in the processing capacity and speed of today's best electronic systems. Fully coherent, complex and high-fidelity optical signal processing will fuel applications in communications, surveillance, pattern recognition, remote sensing, high-speed computing, as well as spectroscopy and quantum control of chemical processes. On page 463 of this issue[1], Zhi Jiang and his colleagues at Purdue University have taken a step towards the goal of building an OAWG device.

The core of an OAWG is a phase-stabilized optical frequency comb that ensures the underlying phase coherence of the optical field. Independent control of the amplitude and phase of multiple frequency-comb lines enables complete control of an output waveform without loss of coherence. Figure 1 schematically depicts the principle of an OAWG, illustrating the importance of maintaining optical phase coherence and manipulating individual spectral windows with a high fidelity.

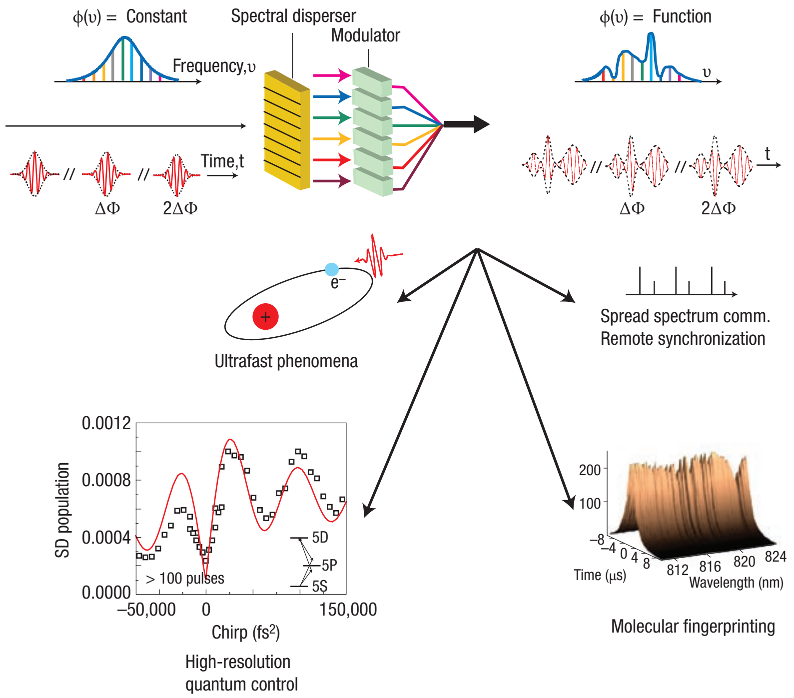

Figure 1 A schematic of an OAWG showing its applications. The OAWG needs to maintain optical phase coherence and requires a massive amount of parallel processing of spectral phase and amplitude. The technology will have a profound impact on a range of important applications. (υ: frequency, t: time; $\Delta\Phi$: pulse-to-pulse carrier-envelope phase offset; $\phi(\upsilon)$: pulse spectral phase)

Optical fields with cutting-edge phase control can now maintain phase coherence over one second. In other words, 10^{15} optical waves can pass by without a single cycle falling out of phase. The recent development of optical frequency combs has enabled this unprecedented control of optical phase coherence to be distributed across the entire visible and infrared regions of the electromagnetic spectrum. It has also led to the direct visualization and measurement of light ripples[2,3].

The comb's unprecedented spectral and temporal precision has already profoundly changed optical frequency metrology and ultrafast science, with breakthrough developments in optical atomic clocks; optical frequency synthesis; united time–frequency spectroscopy; high-resolution quantum control; sub-single-optical-cycle stabilization of pulse trains and carrier-envelope phase; coherent pulse synthesis and amplification; and control of subfemtosecond electron dynamics in atoms and molecules[4].

Given this impressive list of major advances, imagine the power that will be available when we achieve complete control of coherent optical fields. To realize an OAWG, we will not only need to preserve phase coherence across a wide optical spectral bandwidth and over a long period of time, but also to be able to set arbitrary values of amplitude and phase for any prescribed spectral unit cells. Pulse shaping through spectral phase control has been a tool used for coherent-control experiments[5], but typically at low spectral resolution and without regard to the pulse-to-pulse optical phase coherence. In the work by Jiang and colleagues[1], spectral manipulation is performed over an optical frequency comb, with over 100 comb components individually controlled in parallel. Although the number of lines under control is still small, and lie within a fairly limited spectral bandwidth, this work nevertheless represents a significant step towards complete control of coherent light, with the ability to synthesize arbitrary optical waveform pulses with desired shapes and precisely controlled frequencies and phases.

The key advance made by Jiang and co-workers is the high-fidelity, programmable, and line-by-line manipulation of the amplitude and phase of more than 100 individual comb components in a spectral span of about 0.5 THz. In this work, the optical frequency comb was produced on a continuous-wave laser though radiofrequency sideband generation by electro–optic phase modulators. In general, a phase-modulated field has a constant intensity in time. However, as the comb lines with spacing of 5 GHz were resolved in a liquid-crystal-modulator array of 2 × 128 pixels, manipulation of the individual lines was possible. Thus a train of transform-limited picosecond pulses at the 5-GHz repetition rate could be generated. Further spectral broadening and dispersion compensation in a fibre-based soliton compressor produced a 5 GHz train of 270-fs pulses. This conversion of a continuous-wave laser to a train of femtosecond pulses is testimony to the power of line-by-line spectral shaping.

The researchers also demonstrated precise and programmable control of the pulse delay, without the use of a traditional mechanical delay line. This control was accomplished by the application of linear spectral phase by the liquid-crystal modulator, leading to a pure delay that had a dynamic range of the entire pulse repetition period. Such a large range of precise delay control is possible only when individual comb components are manipulated.

Simultaneous intensity and phase control of individual comb components achieved by Jiang *et al.* has allowed a trial demonstration of an OAWG, albeit with limited bandwidth and complexity. The original pulse spectrum was split into two halves, and a linear spectral phase was applied to one half and a cubic spectral phase was applied to the other. The resultant complex waveform split each original pulse into two, one of which was delayed and the other had a complex pulse shape. The high fidelity of this OAWG process is remarkable, with every tiny feature of the waveform accounted for by theoretical simulations.

Precise control and synthesis of arbitrary optical waveforms represents a dramatic upgrade from radiofrequency and microwave technologies. A few examples of applications include spectacular increases in communication capacity and covertness; high-fidelity data generation and transmission; remote synchronization by means of ultrastable clock signals[6]; advanced analog-to-digital and digital-to-analog conversion; synthetic aperture optics; precision quantum control[7]; novel spectroscopy and trace sensing[8,9,10]; and control of ultrafast processes in atoms and molecules, among many others.

A desirable feature of the OAWG is the ability to synthesize complex electromagnetic waveforms of any imaginable shape and frequency composition. To achieve this, a new technology for optical waveform synthesis needs to be developed. First, the bandwidth of the OAWG must be expanded to hundreds of terahertz, and optical radiation needs to be generated and controlled in a fully phase-coherent fashion. Independent control of the amplitude and phase of each spectral component would require extensive parallel modulators and multiplexers to function simultaneously[11], with update rates approaching the repetition frequency of the comb system. Robust techniques are needed to stitch together independently produced waveforms into coherent time structures that cover the range from a single optical cycle to the entire pulse period. Finally, we need to develop ultrabroadband detectors for converting measured waveforms into information content with high fidelity. The road ahead is certainly exciting but challenging.

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