Rapid optical data processing in the frequency domain

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Manipulating optical waveforms in the frequency domain enables terahertz signal processing and overcomes switching speed limitations.

Demand for high-speed signal processing continues to grow, and the speeds required are increasing even to terabit per second levels. However, electronic devices have an effective maximum cut-off frequency of 100GHz (switching speed), determined by the movement of electrons across semiconductor junctions, which makes it difficult to achieve Tbit/s data transmission. Optical signal processing offers higher frequencies and faster data transmission, but sufficiently rapid data processing is challenging. One way forward is to manipulate signal waveforms in the frequency domain.

Modulating the phase of a reference signal is one way to encode and transmit information, and it is efficient to transmit multiple signals simultaneously. These aims can be achieved by multi-level phase shift modulation keying and wavelength-division multiplexers, respectively.\(^1\) Unscrambling the received signals and extracting information requires us to reverse Fourier transform the waveform to extract both amplitude and phase information for multiple frequencies.

An optical frequency comb (OFC) measures individual quantities of particular frequencies of light in a mixture. The shape of the waveform is controlled by the relative phases of the optical longitudinal modes (i.e., frequencies favored by the transmission medium). We previously proposed a method for spectral control of an OFC, which can overcome the limitations of the switching speed.\(^2,3\) More recently, we developed a digital-holographic technique called dual-heterodyne mixing,\(^4,5\) which can measure the relative phases in the OFC.

To demonstrate how the amplitude and phase spectra of a signal change over time, we first showed how the amplitude and phase spectra are obtained from a source OFC: see Figure 1.\(^5\) Inverse Fourier transformation of the OFC shows the waveform with this amplitude, frequency, and phase: see Figure 2. We used our proposed technique to obtain the amplitude and phase electric field evolutions. We began by slicing the electric field waveform into 100fs segments, each of which was then Fourier transformed to obtain the electric field spectral evolution: see Figure 3. This showed that there are five major frequencies present, and the amplitude and phase of each changes over time: see the colors in Figure 3(a) and (b) for the amplitude and phase, respectively. For example, the peak pulse at the center of Figure 3(a) is almost chirpless in Figure 3(b)—that is, the phase variation in the square region at the center of the image is small—which is difficult to see in Figure 1.

In the second part of our work, we showed that with dual-heterodyne mixing we can control and analyze the amplitude and phase of each tooth in an OFC with an ultrafast (THz frequency range) OFC synthesizer (UOFCS) and also analyze the amplitude and relative phase of each tooth of the signal OFC with an ultra-fast optical frequency analyzer (UOFCA).

The UOFCS incorporates an arrayed waveguide grating (AWG) and multi-channel amplitude and phase modulators. The time resolution of the waveform output from the synthesizer is inversely proportional to its frequency band. However, the number of channels the AWG can process in parallel is limited. We therefore integrated a custom sinusoidal AWG to act as a filter and extract a 400GHz OFC signal (OFCs) from a 25GHz comb. The 400GHz OFC was incident on the UOFCS, which manipulated the amplitude and phase of each longitudinal mode: see Figure 4.

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We used the UOFCS to send 4bit packets—that is, packets of four 0.5ps pulses that are either on (1) or off (0), representing binary signals 1000, 1010, 1110, and 1100—and tested whether we could use dual heterodyne mixing to receive them correctly with the UOFCA. The signals were successfully obtained: see Figure 5. The time window and resolution of the synthesized waveform are determined by the OFC peak interval and OFC frequency band, respectively. As a result, all signals at 400GHz

Figure 2. Intensity profile obtained by experiment. a.u.: Arbitrary units.

Figure 3. Dual-heterodyne mixing trace of (left) amplitude and (right) phase spectral evolution.

Figure 4. Custom waveform synthesizer.

Figure 5. 2Tbit/s (4bit) packets obtained from the measured phase and amplitude spectra. The measured packet patterns (a) 1000, (b) 1010, (c) 1110, and (d) 1100 are shown as waveforms filled in red, with numerically obtained waveforms shown as solid blue lines.

Figure 6. Operating principle of the holographic optical frequency comb (OFC) analyzer. The spectra of relative phase and amplitude can be measured in parallel. a_n: Amplitude of nth longitudinal mode of OFC. \( \phi_n \): Phase of nth mode. OFC_r: Reference OFC. OFC_s: Signal OFC. \( f_n \): Optical frequency of nth signal mode. \( \Delta f \): Comb tooth interval. \( f_{rn} \): Optical frequency of nth reference longitudinal mode. \( \delta f \): Optical frequency offset between OFC_s and OFC_r. AWG: Arrayed waveguide grating. OFC: Optical frequency comb. DC-n: nth electric DC signal. \( \Delta \phi_n \): Relative phase between nth and (n+1)th modes in OFC_s.
OFC were modulated by control signals at least as long as the time inverse of 400GHz (i.e., 2.5ps). Rather than require a ~450fs switching period (the inverse of OFC frequency band 2THz), we could process data pulses of that duration with much longer control signals. In addition, the bit number is determined by the number of peaks in the OFC. In other words, an OFC with four frequencies is required for a 4bit signal, and we have already succeeded in generating 32bit signals from 32 frequencies in the lab.

The UOFCA compares the signal OFC with a reference OFC (OFC_r) that has a slightly offset central frequency but the same (frequency) gap $\Delta f$ between the component frequencies (i.e., the teeth of the comb). A parallel detection system measures the signal spectral waveform—the amplitudes—and detects the beats between the neighboring frequencies of the two combs. It then analyzes the beats to obtain the phases of the signal components relative to the OFC_r, which has known phases (see Figure 6).

In summary, our proposed system can divide signal information by frequency rather than time. Using our UFOCS and UOFCA, we have successfully synthesized, sent, received, and analyzed 2Tbit/s optical waveforms, which is a substantial increase in speed over the effective electronic signal processing of 100GHz. We are now working to apply our method not only to optical communication technology but also to other systems requiring rapid spectral analysis.

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References