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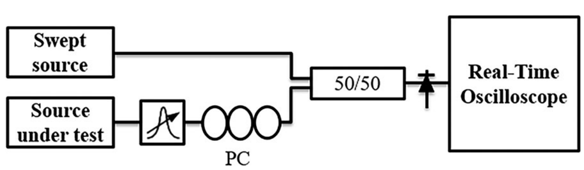

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Fast-Recovery of the Amplitude and Phase of Short Optical Pulses Using a Frequency-Swept Source Based Heterodyne Measurement

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Abstract: We propose a very fast heterodyne technique to recover the amplitude and phase of short optical pulses generated, e.g., by a mode-locked laser. A linearly swept frequency source is used to scan the entire optical spectrum of the mode-locked laser in a single continuous sweep. The beat signal is recorded on a fast oscilloscope and then digitally processed allowing the simultaneous recovery of the amplitude and the phase. This measurement is fast (less than 2 μs) and requires no prior spectral information about the signal under test.

Index Terms: Ultrafast measurements, phase measurement, tunable laser.

1. Introduction

Ultrashort laser pulses have found various applications from optical communication [1]–[3] to optical imaging [4], [5]. The rapid development of these applications in recent years led research to focus on the measurement of the intensity and phase of the ultrashort pulses to characterize the complex spectrum and then reconstruct the temporal pulse shape. Various techniques have been proposed for this purpose, such as optical autocorrelation [6], [7], frequency-resolved optical gating (FROG) [8], [9] or spectral phase interferometry for direct electric-field reconstruction (SPIDER) [10], [11]. However, these techniques, despite being the most widely used, require sufficiently high signal power by using EDFAs as in [12] which may cause spectral distortion making the measurement inaccurate. Recently, Reid et al, have demonstrated the stepped-heterodyne measurement [13] that consists in mixing the signal under test with a single mode local oscillator positioned between two of the signal modes. The beat signal allows the recovery of amplitude of the two modes and their

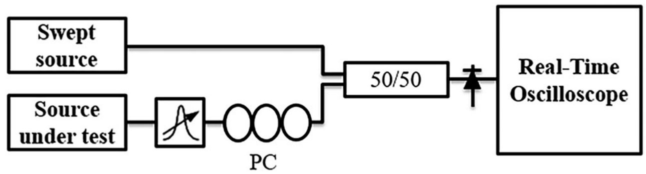

Fig. 1. Experimental setup for the heterodyne measurement. The passive coupler is used to mix the signal under test with the swept source signal. PC represents a polarization controller.

phase difference. By repeating this measurement for various wavelengths of the local oscillator placed between the signal modes, one can obtain all consecutive phase differences and recover the phase of each mode.

This stepped-heterodyne measurement needs no electronic clock or optical modulation of the signal which makes it a simple and straightforward technique. Nevertheless, it requires repeating the procedure as many times as the number of modes of the signal under test which, in case of a laser with hundreds of modes, may take a long time. An alternative approach was proposed by Butler et al, [14] which consists in replacing the local oscillator by an optical comb allowing the record of the complex spectrum in a single shot.

However, both techniques require a prior knowledge of the spectral information such as repetition rate, the number of modes as well as their exact frequencies in order to position the local oscillator or the optical comb at the right frequency. In this letter, we present a new simple approach based on the stepped-heterodyne technique where an optical frequency-swept source is used instead of the local oscillator. The linearly swept source permits to scan the entire optical spectrum of the signal in a single continuous sweep. The signal under test is mixed with the optical swept source modes while the beat signal is recorded on a fast oscilloscope.

2. Experimental Details

The experimental setup is presented in Fig. 1, the source under test used in this study is a 4 mm long single section quantum-dash mode-locked laser diode (QDash-MLLD) [15] with a repetition rate of 10 GHz at 300 mA. We also used a tunable bandpass filter with a bandwidth of 2 nm at the laser output to select few modes. For the swept source, we used a sampled-grating distributed Bragg reflector (SG-DBR) tunable laser [16] that can linearly scan a 50 nm bandwidth centered at 1550 nm. A relatively fast sweep rate of 20 kHz is adopted and a real-time oscilloscope allows recording the beat signal with a sampling frequency of 40 GSa/s.

Assuming that the signal under test is periodic [13], the complex electric field can be written as:

$$E_{sig}(t) = \sum_{n=0}^{m} \sqrt{P_n} \exp\left(jn\Omega t + j\phi_n\right) \exp\left(j\omega_{sig} t + j\phi_{sig}(t)\right) \tag{1}$$

where $\Omega = 2\pi F$ and F is the repetition rate of the signal, P_n and ϕ_n are the power and the spectral phase of the nth mode respectively. ω_{sig} and $\phi_{sig}(t)$ are the frequency and the phase noise of the optical carrier respectively.

The complex electric field of a linearly swept source can be written as:

$$E_{ss}(t) = \sqrt{P_{ss}} \exp\left(j2\pi(\nu_0 + \frac{\gamma}{2}t)t + j\phi_{ss}(t)\right) \tag{2}$$

where $\nu(t) = \nu_0 + \gamma t$ is the instantaneous optical frequency of the swept source, and P_{ss} and $\phi_{ss}(t)$ the power and the phase noise respectively.

Fig. 2 shows the time-frequency representation of the swept source. The frequency varies linearly while covering all spectral components of the signal under test.

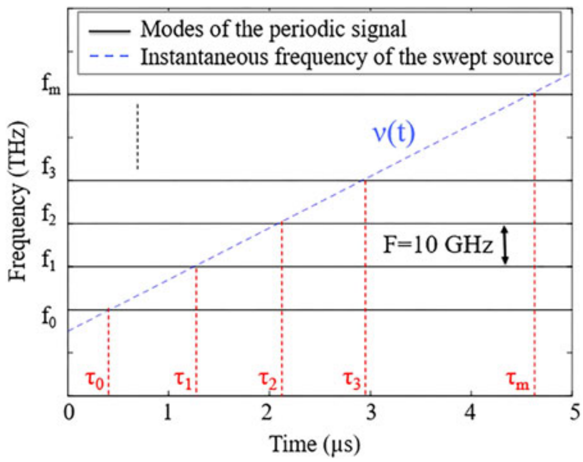

Fig. 2. Time-frequency representation of the signal modes (black) and swept source (blue dashed). The swept source frequency varies linearly in time allowing the beating with all modes in a single shot. $(\tau_0, \tau_1, \tau_2, \ldots\tau_m)$ represent the times when the swept source is at the same frequency as the modes $(0, 1, 2, \ldots m)$. (red dashed).

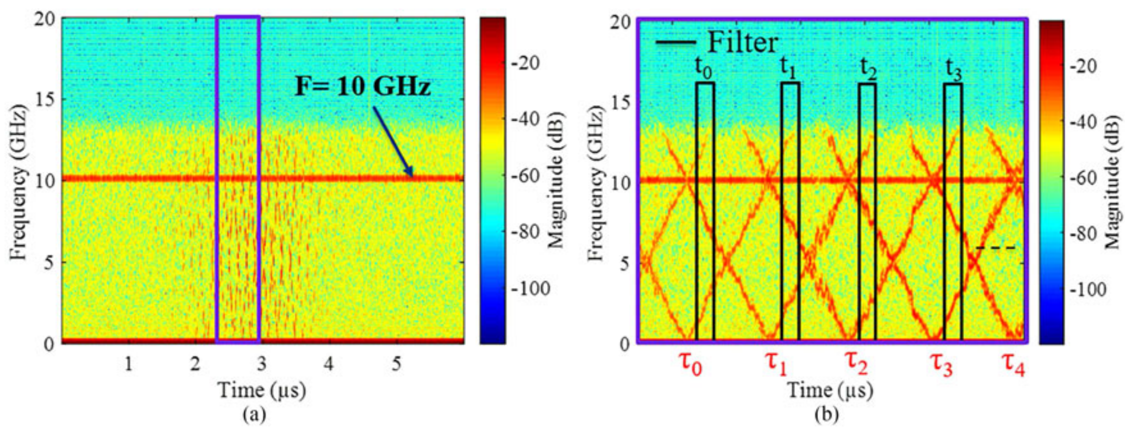

Fig. 3. (a) Spectrogram of the beat signal. (b) Zooming in. The spectrogram shows the instantaneous beat frequency. The repetition rate $F = 10$ GHz can be deduced from (a). The beat signal will be filtered out at every time corresponding to an instantaneous frequency lower than half the repetition rate as shown in (b) (black).

When the two signals are mixed, the complex electric field of the resulting signal can be written as:

$$E_{beat}(t) = \frac{1}{2}(E_{sig}(t) + E_{ss}(t)) \tag{3}$$

The beat signal is detected in the RF domain using a photodiode with a bandwidth of detection larger than the repetition rate of the signal under test.

A spectral analysis is then performed on the resulting signal with a short-time Fourier transform (STFT) [17] as shown in Fig. 3. This allows the recovery of the instantaneous beat frequency which gives direct access to the exact frequency of each mode in addition to the repetition rate of the signal.

From the spectrogram of the beat signal and the time-frequency representation of the swept source, we can have all spectral information about the signal under test. The repetition rate $F = 10$ GHz is deduced from Fig. 3(a).

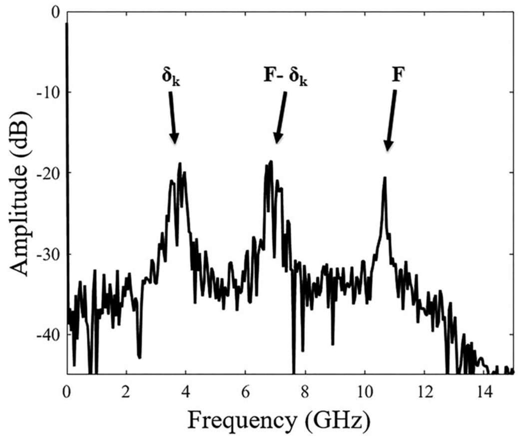

Fig. 4. RF beat spectrum of the filtered signal Sig_k. δ_k and $F - \delta_k$ are the beat frequencies between the swept source and the kth and $(k+1)$th modes respectively. F is the repetition rate.

The number of modes is given by the number of times $(\tau_0, \tau_1, \tau_2, ...\tau_m)$ corresponding each time the beat frequency equals 0 as shown in Fig. 3(b). The frequency of each mode can be deduced from Fig. 2.

Once all spectral components are well known, we filter out the beat signal at $(t_0, t_1, t_2, ...t_{m-1})$ corresponding to an instantaneous frequency lower than half the repetition rate as shown in Fig. 3(b).

Each of the m filtered signal represents a beating between the swept source and two adjacent modes. So, the kth signal located between the modes k and $k+1$ can be considered as the sum of three signals at the RF frequencies: δ_k, $F - \delta_k$ and F respectively.

$$Sig_k = Sig_{\delta_k} + Sig_{F-\delta_k} + Sig_F + DC \tag{4}$$

where δ_k represents the frequency difference between the swept source and the kth mode as shown in Fig. 4.

Note that we do not consider the RF frequencies higher than F because of the bandwidth limit of detection of the photodiode.

The three signals can be written as:

$$Sig_{\delta_k} = \sqrt{P_{ss}P_k}\exp\left(j(2\pi t(\delta_k + \frac{\gamma}{2}t) + \phi_{ss}(t) - \phi_{sig}(t) - \phi_k)\right) \tag{5}$$

$$Sig_{F-\delta_k} = \sqrt{P_{ss}P_{k+1}}\exp\left(j(2\pi t((F-\delta_k) - \frac{\gamma}{2}t) - \phi_{ss}(t) + \phi_{sig}(t) + \phi_{k+1})\right) \tag{6}$$

$$Sig_F = P_{tot}\exp\left(j(2\pi Ft + \phi_{tot})\right) \tag{7}$$

where Sig_{δ_k} and $Sig_{F-\delta_k}$ represent the beat signal between the swept source and the kth and $(k+1)$th modes respectively. While Sig_F is the sum of all beat signals between adjacent modes.

Fig. 4 represents the RF spectrum of the filtered beat signal Sig_k. We can clearly distinguish the three spectral components at δ_k, $F - \delta_k$ and F respectively.

From Fig. 4, we can filter the three signals Sig_{δ_k}, $Sig_{F-\delta_k}$ and Sig_F.

In order to cancel the phase noise, we multiply the Eq. (5) by Eq. (6) which gives:

$$Sig_{\delta_k}Sig_{F-\delta_k} = P_{ss}\sqrt{P_kP_{k+1}}\exp\left(j(2\pi Ft + \phi_{k+1} - \phi_k)\right) \tag{8}$$

To extract the phase difference between the kth and $(k+1)$th modes, we multiply Eq. (8) by the complex conjugate of Sig_F which leads to:

$$Sig_{\delta_k}Sig_{F-\delta_k}\overline{Sig_F} \propto \exp\left(\phi_{k+1} - \phi_k - \phi_{tot}\right) \tag{9}$$

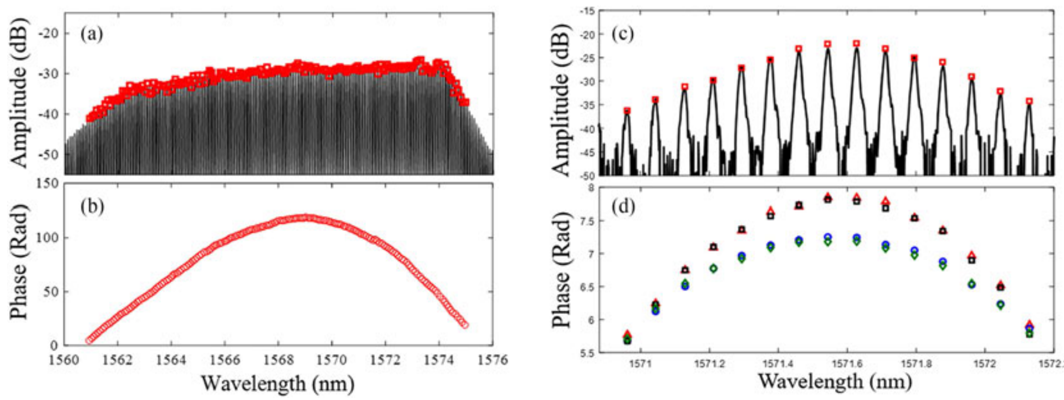

Fig. 5. (a) Spectral amplitude without filter (red square) and optical spectrum of the laser measured with an optical spectrum analyzer (black). (b) Spectral phase (red circles). (c) Spectral amplitude after filter (red square) and the optical spectrum measured with an OSA (black). (d) Spectral phase measured directly at the filter output (red triangles) (black squares) and after 100 m of SMF (blue circles) (green diamonds) using our technique and the stepped-heterodyne technique respectively.

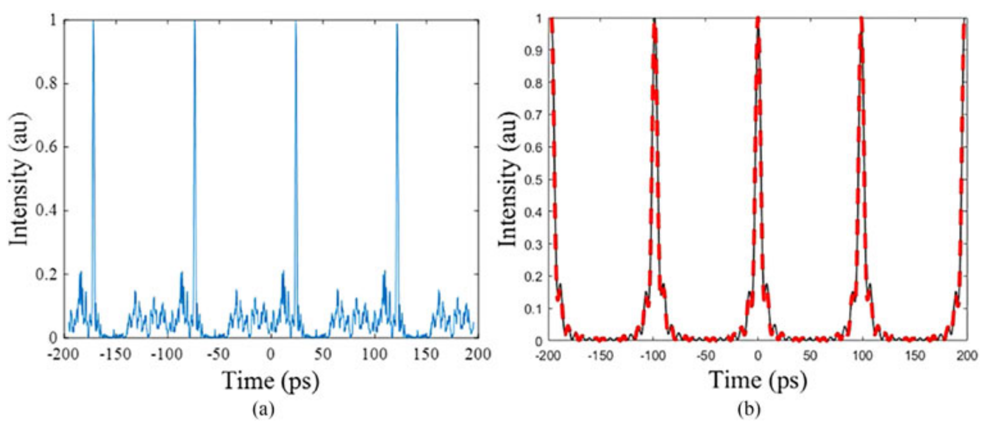

Fig. 6. (a) The temporal pulse directly at the output of the laser without using the filter (blue). (b) The temporal pulse at the filter output using continuous swept source (black) and using the stepped-heterodyne technique (red).

The presence of ϕ_{tot} will introduce a temporal shift of the reconstructed pulse and will not affect the measurement.

Note that this entire process is applied simultaneously to all m filtered signals allowing the recovery of the amplitude of all modes as well as the phase difference between consecutive modes in a single measurement. This measurement is fast (less than 2 μs) and is proportional to the sweep rate of the swept source.

3. Results and Discussion

Fig. 5(a) and (b) show the measurement of the spectral amplitude and phase of the laser without filter (170 *modes*). The DC drive current used is 300 mA and the coupled output power is 2 mW. The recovered pulse shape is shown in Fig. 6(a). We do not get a clean pulse shape due to the strong intracavity dispersion of the laser [15]. So, we used an optical filter in order to select few modes. Fig. 5(c) and (d) represent the measurement of the spectral amplitude and phase using the filter. (d) is the spectral phase measured directly at the filter output (red triangles) and after propagation through 100 m of SMF (blue circles) to show the effect of a well-known value of dispersion on the

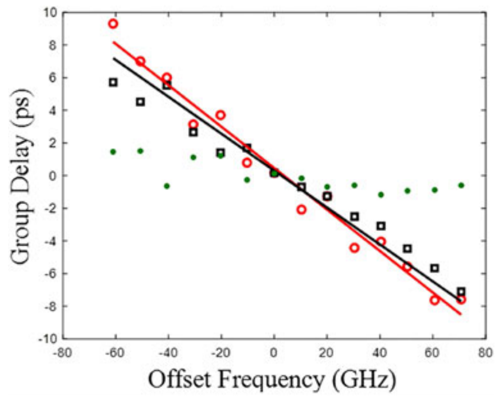

Fig. 7. Group delay measured directly at the filter output (red circles), after 100 m of SMF (black squares), linear fit (red line), predicted group delay after 100 m of SMF using 17 ps/nm.km of dispersion (black line). The standard error is less than 1.5 ps (green dots).

spectral phase. The same measurements have been done using the standard stepped-heterodyne technique (black squares) and (green diamonds) to demonstrate our technique.

From Fig. 5, we can see that the measured spectral amplitude matches that obtained with an optical spectrum analyzer (OSA) while the spectral phase shows good agreement between our technique and the stepped-heterodyne one.

Once, we the amplitude and phase of all modes is recovered, we can finally reconstruct the temporal pulse using our technique (black) and the stepped-heterodyne (red) as shown in Fig. 6 (b) We observe that both techniques give similar result.

The group delay of the signal is calculated by deriving the spectral phase with respect to the angular frequency.

Fig. 7 represents the measured group delay directly at the filter output (red circles) and after 100 m of SMF (black squares). The (red line) is the linear fit of the group delay directly at the filter output and the (black line) is the predicted group delay after 100 m SMF using 17 ps/nm.km of dispersion. The difference between the measured and the predicted group delay is the standard error and it is represented in (green dots). The standard error is less than 1.5 ps.

4. Conclusion

In conclusion, a novel heterodyne technique has been presented that allows the measurement of the amplitude and the phase of periodic optical signals using a frequency swept source. In addition to all stepped-heterodyne advantages, this technique does not require any prior information about the repetition rate of the signal under test, the number of modes and their positions. We have shown how this spectral information could be extracted from the beat signal by using a Short-time Fourier transform. The amplitude of all modes as well as the phase difference between adjacent modes are recovered simultaneously by filtering the beat signal at each time corresponding to an instantaneous frequency lower than half of the repetition rate which means that only one measurement is needed to reconstruct the temporal pulse. Finally, this measurement is fast (less than 2 μs) and is limited only by the sweep rate of the swept source, which makes it very suitable for real-time analysis and control of fast signals.

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