A Rate-Doubled 10-GHz Fiducial Comb Generator for Precision Optical Timing Calibration

Introduction

High-energy-density plasma experiments conducted at LLE[1] utilize a ROSS (Rochester Optical Streak System)[2] streak camera as a primary recording device to time resolve subnanosecond events. These measurements include P510 streak-camera OMEGA beam diagnostics,[3] the velocity interferometer system for any reflector (VISAR)[4] to measure shock-front propagation, the neutron temporal diagnostic (NTD)[5] to measure the fusion-reaction–rate history of neutrons for inertial confinement fusion (ICF)[6] experiments, and the Thompson scattering system (TSS)[7] to analyze scattered light (λ = 190 nm to 850 nm) generated during target shots. Time-base calibration for the streak cameras at the ~1% level is desired for these experiments. The analog electrical waveforms applied to the streak-tube deflection plates are inherently nonlinear. Variations in the sweep rate across the output phosphor screen are of the order of 10% to 15%. Experiments with measurement duration times of less than a few nanoseconds require faster fiducial comb rates than are currently available for accurate time-base calibration. This calibration standard need motivated the development of the 5-GHz comb generator and corresponding optical rate doubler presented here.

Comb Generator Design

A 5-GHz externally optical rate-doubled fiducial comb generator was developed with four selectable comb pulse rates and a corresponding optical rate doubler to produce a 10-GHz pulse rate. This is a self-contained and portable generator that is useful for many types of optical timing calibration needs. The comb generator is shown in Fig. 155.31. The output is fiber optic coupled at a wavelength of 680 nm (visible red) with a nearly Gaussian pulse shape. The peak pulse output power is ~5 mW. A low-phase-noise microwave drive source provides low pulse-to-pulse jitter. The output rate can be synchronized to an externally supplied reference standard frequency source. An internal reference frequency crystal oscillator is incorporated for stand-alone operation.

The light pulses from the comb generator are produced by a solid-state vertical-cavity, surface-emitting laser (VCSEL).

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Figure 155.31
The 5-GHz comb generator is a portable self-contained calibration instrument.

These solid-state lasers are primarily used for high-bandwidth fiber-optic communications transmitting sources. VCSEL's have the advantages of being solid state, small, cost effective, and straightforward to couple to fiber-optic media. The increasing need for higher data rates has prompted the development and availability of VCSEL's that support higher modulation bandwidths. These higher-bandwidth VCSEL's can be directly applied in the development of fiducial comb generators when driven by a sine-wave microwave signal in place of a communication data stream. The VCSEL used for this design is rated for 10-GB/s data rates, or 5-GHz modulation. The output is centered at a wavelength of 680 nm (visible red).[8] The peak pulse output power is ~5 mW. The VCSEL output is coupled with a fiber-optic launcher to a 100-μm-diam fiber. For streak-camera sweep calibration, the fiber output is imaged onto the photocathode.

In the communications integrated circuit (IC) industry, a variety of manufacturers provide high-bandwidth VCSEL drivers to modulate the light produced by a VCSEL in accordance to a digital data stream applied to the input of the driver. It was our experience, however, that commercially available IC drivers were better suited to continuous data streams than a burst of a microwave sinusoid needed for the fiducial comb picket application. A burst of fiducial picket pulses, instead of a steady stream of pulses, is utilized to prevent excessive illumination and blooming of the streak-camera photocathode onto the imager, thereby obscuring desired diagnostic data or potentially damaging the streak camera. The comb fiducial burst is driven to be on only when the camera sweeps.

The block diagram of a fiducial comb generator is shown in Fig. 155.32. The main components of the fiducial comb generator are (1) the low-phase-noise, phase-locked loop (PLL) 5-GHz microwave modulation source; (2) the rate-selection frequency divider and filter network; (3) the microwave VCSEL driver amplifier; (4) the VCSEL bias driver/duty cycle switch; and (5) the fiber-coupled VCSEL. Additional functional blocks represent operational control, primary dc power, VCSEL temperature stabilization, output-pulse triggering, and an internal PLL reference frequency source.

The 5-GHz PLL microwave modulation source is a phase-locked dielectric resonator oscillator (PDRO).[9] This is a low-noise oscillator with phase-locked loop frequency control that locks the output frequency to an integer multiple of the reference frequency input. The reference frequency used is 75.997870 MHz, twice the 37.998935-MHz reference frequency for LLE's OMEGA and OMEGA EP Hardware Timing Systems. This reference frequency can be either externally sourced or internally sourced from a temperature-stabilized crystal oscillator. The phase-locked loop multiplier is $N = 66$ to produce a PDRO output frequency of 5.0159 GHz. Table 155.III lists the manufacturer's specified phase-noise characteristics of the PDRO when locked to a low-noise reference frequency source. Utilizing Eq. (1) from Ref. 10, phase-noise sideband energy can be converted to equivalent rms jitter assuming no amplitude modulation (AM) contribution to the sideband energy exists:

$$\sigma_{\text{jitter}}[\text{s}] = \frac{\sqrt{2 \cdot \int_0^{\infty} S(f)\,\mathrm{d}f}}{2\pi f_0}. \tag{1}$$

In Eq. (1), $S(f)$ is the phase-noise sideband power in W/Hz as a function of frequency separation from the center frequency, f_0. $S(f)$ is integrated over the total single sideband frequency

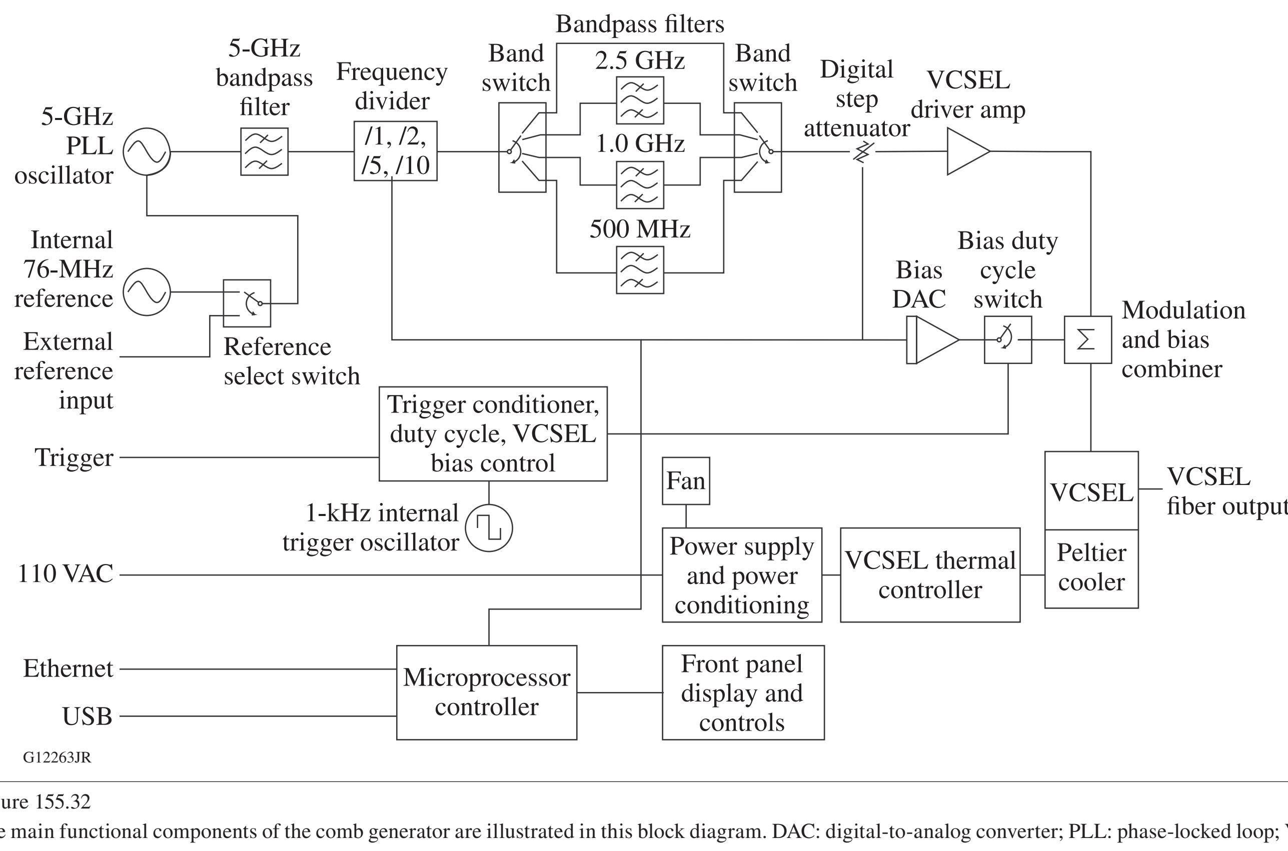

Figure 155.32
The main functional components of the comb generator are illustrated in this block diagram. DAC: digital-to-analog converter; PLL: phase-locked loop; VAC: volts ac; VCSEL: vertical-cavity, surface-emitting laser.

range. The square root of twice this value (to include both sidebands) is equal to the rms phase jitter in radians for small values of phase deviation. This result is converted to rms jitter in seconds by dividing by the radian center frequency of the signal source. Utilizing the values specified for phase noise for the phase-locked 5.0159-GHz oscillator from Table 155.III, the output jitter using a low-noise 76-MHz reference is ~0.1-ps rms. Future measurements on production comb generators will be performed to verify this result.

Table 155.III: Phase-noise specification of the phase-locked 5-GHz dielectric resonator oscillator (PDRO) with a low-noise, 76-MHz crystal oscillator reference source.

Distance from Center Frequency	Phase Noise (dBm/Hz)
100 Hz	–68
1 kHz	–98
10 kHz	–113
20 kHz	–113
100 kHz[a]	–113

[a]Above 100 kHz the contribution to the phase-noise power integral is insignificant.

1. VCSEL Source and Rate Divider

The phase-locked oscillator output passes through a selectable rate divider and corresponding filter network to provide four comb rates with lower rates to accommodate applications that require longer pulse spacing. The divider can be set to four values: 1 (5.0159 GHz), 2 (2.5079 GHz), 5 (1.0032 GHz), and 10 (501.59 MHz). These modulation frequencies produce comb light pulse spacings of 199.4 ps, 398.7 ps, 996.8 ps, and 1.994 ns, respectively. The filter network following the divider has selectable bandpass filters that are centered at the selected divider output rate to remove harmonics, subharmonics, and spurious products at the desired frequency. The filtered signal passes through a broadband VCSEL driver amplification stage. The driver amplifier produces a level sufficient to modulate the amplitude of the VCSEL from the "off" to the "on" state when a dc bias is applied that is just below the VCSEL on-state threshold current. A programmable attenuator is included preceding the VCSEL driver amplifier, which allows one to adjust the modulation level to the VCSEL. Modulating the VCSEL with a sine-wave drive produces a nearly Gaussian output light pulse shape.

2. VCSEL Bias

The VCSEL bias is a rectangular pulsed bias source that is combined with the microwave driver modulation signal through a microwave resistive combiner. The bias signal has two purposes: (1) to bias the VCSEL just below the on-state threshold current to reduce modulation latency; and (2) to set a fixed pulse burst duration to limit the laser on time, preventing intensity edge blooming on the streak camera prior to and following the streak sweep. The modulation and bias pulses are set so that neither one alone will illuminate the VCSEL independently, but only when combined together will the VCSEL produce a modulated light output. Both the duration and amplitude of the bias pulse are adjustable. The bias pulse is initiated by selecting operation from an external trigger or internally by a continuous 1-kHz repetition-rate trigger.

To improve VSCEL output efficiency, a thermoelectric Peltier cooler is mechanically connected to the VCSEL, which stabilizes its temperature to 20°C. The 680-nm modulated output of the VCSEL is coupled into a 100-μm-diam fiber. The fiber output is available at an SC connector on the front panel of the comb generator.

3. Control

Control of the comb generator is accomplished via the front panel (Fig. 155.31) or through a serial communications interface (Ethernet or USB). The front panel controls provide access to the settings required to monitor and optimize comb performance for each rate. Each output rate can have unique settings for modulation level, bias level, and burst duration. These are stored and automatically retrieved upon power up.

Remote control can be accomplished in two ways: An internal web page with setting-entry boxes and operation monitor displays is available through a unique URL address for the generator. The control page of the web interface is illustrated in Fig. 155.33. All operational controls can be accessed through this page including operation fault threshold settings. The comb generator can also be controlled by ASCII text string commands through the Ethernet or USB ports.

4. Output Rate-Doubling Option

An external optical pulse doubler can be added to the VCSEL output from the front panel to reduce the comb pulse spacing to 99.7 ps (Ref. 11). The optical ray trace in Fig. 155.34 illustrates the principle of operation. The *f*/2.5 randomly polarized output of the fiber is collimated using a molded aspheric lens. A polarizing cube splits the collimated beam into equal-energy *p*- and *s*-polarization paths. Separation based on polarization provides high throughput when the beam paths recombine at the output cube splitter, which would not be the case with dichroic beam splitters. The *p*-polarization path is transmitted through the input and output polarizing cubes and

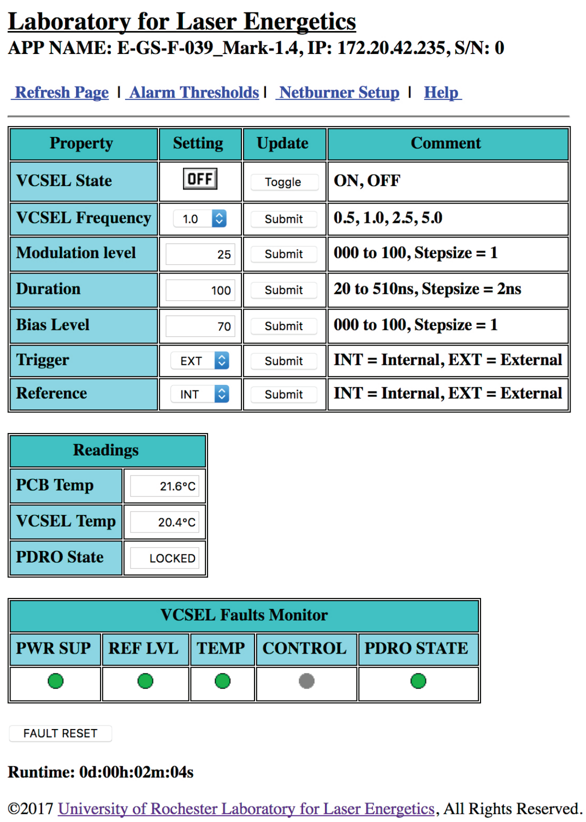

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Figure 155.33
The comb generator web interface page allows one to remotely access all controls.

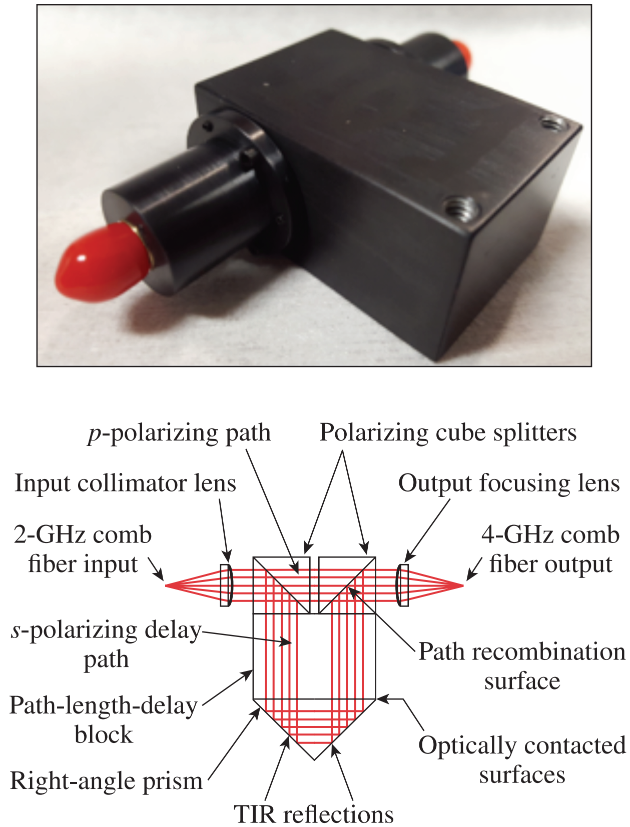

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Figure 155.34
The 5-GHz input comb is split into *p*- and *s*-polarization paths. The *s*-polarization path is time delayed and recombined with the *p*-polarization path. The interleaved 10-GHz comb is focused into the output fiber. TIR: total internal reflection.

is focused into the output fiber via a matching aspheric lens; all surfaces are antireflection (AR) coated. The aspheric lens pair forms a diffraction-limited unity magnification *f*/2.5 relay from the input fiber to the output fiber. The input cube reflects the *s*-polarization path at 90°. The exiting surface of the cube is bonded to the path-length-delay block using index-matching epoxy. The path-length-delay block is optically contacted to the hypotenuse of a right-angle prism used to transport the beam back through the glass delay block using total internal reflection (TIR) at the prism to air uncoated surface interfaces. The path-length-delay block is sized appropriately to retard the beam propagation time by half the 5-GHz rate ±0.5 ps relative to the straight-through *p*-polarization path. The two beam paths are recombined at the output polarizing cube and focused into the output fiber. The use of AR coatings, optically contacted surfaces, and TIR minimizes throughput losses. The aspheric lenses, the polarization cube splitters, and the right-angle prism are off-the-shelf components. The path-length-delay block was custom fabricated to the required length and aperture. The resulting doubler output rate is 10.0318 GHz.

Performance Results

Tests of the 5-GHz comb generator on the ROSS streak camera have been performed. The light output pulse from the comb generator is nearly Gaussian with a full width at half maximum (FWHM) of ~48 ps as illustrated in the lineout from the ROSS streak camera in Fig. 155.35. Figure 155.36 shows the streak-camera imager output with a 5.0159-GHz comb rate compared to a 1.976-GHz comb rate from a Sydor Technologies 2-GHz comb generator streaked simultaneously. Figure 155.37 shows the lineout of pixel counts versus time of the 5-GHz streak from Fig. 155.36. The output power of the 5.0159-GHz pulses was measured with an Ophir-Spiricon PD300 photodiode integrating power sensor over a 50-ns comb pulse burst. The total integrated energy over the burst was 65 pJ for 251 pulses, giving an average energy per pulse of 0.259 pJ. For a Gaussian-shaped energy profile with a FWHM of ~48 ps, the peak power of an individual comb pulse is ~5.1 mW.

Figures 155.38–155.40 illustrate the measured ROSS streak-camera performance for the other three selectable comb generator rates: 2.5079 GHz, 1.0032 GHz, and 501.59 MHz. Figure 155.41 illustrates a measurement of the externally optical rate doubled output at 10.0318 GHz.

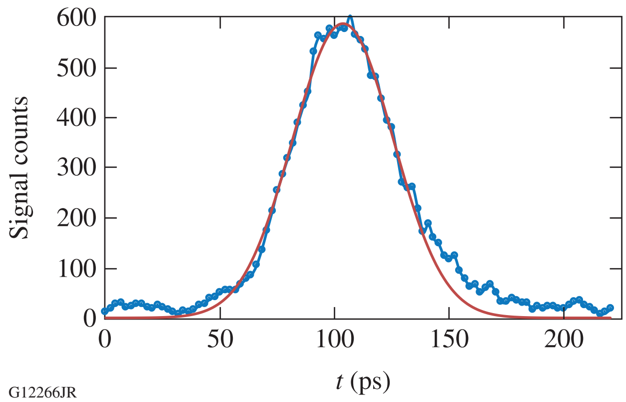

Figure 155.35
The 5.0159-GHz comb generator light pulse shape is nearly Gaussian. The horizontal axis is time, and the vertical axis is the relative pixel count from the imager. The red curve represents the measured lineout data, and the solid blue curve is a best-fit Gaussian profile.

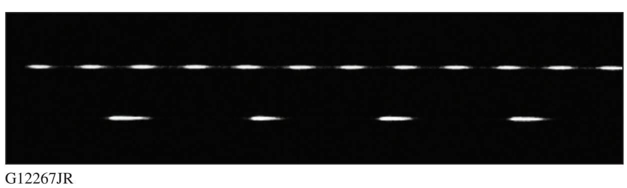

Figure 155.36
Imager display of the 5.0159-GHz comb (top trace) compared to the Sydor Technologies 1.976-GHz comb (bottom trace) on a 2.2-ns ROSS sweep.

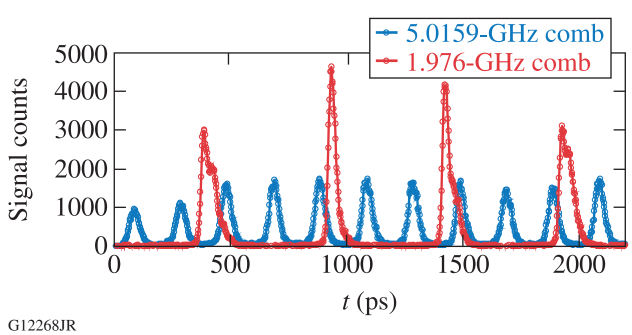

Figure 155.37
Pixel counts versus time for the 5.0159-GHz streak in Fig. 155.36.

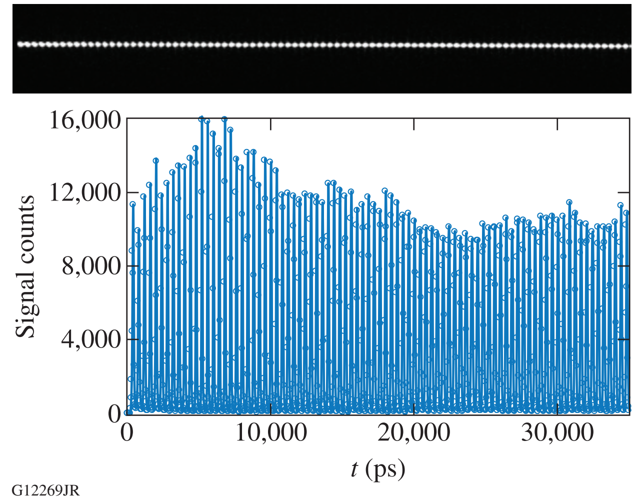

Figure 155.38
The 2.5079-GHz output on a 35-ns streak camera sweep with lineout.

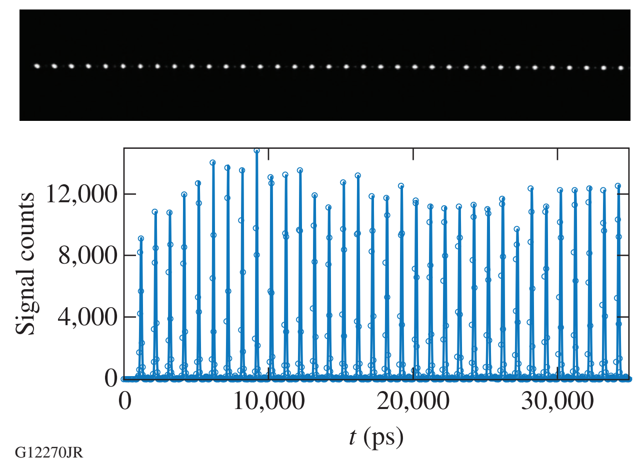

Figure 155.39
The 1.0032-GHz output on a 35-ns streak-camera sweep with lineout.

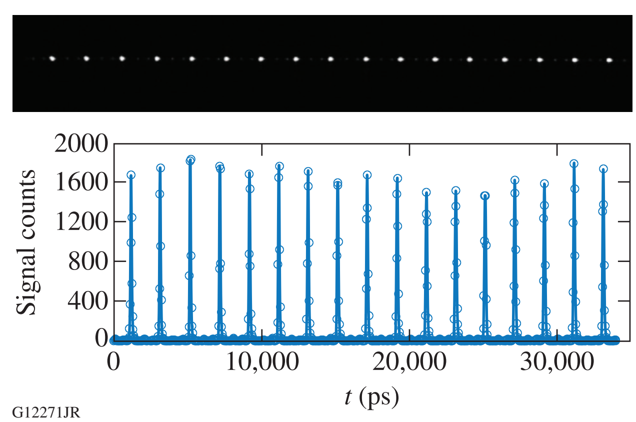

Figure 155.40
The 501.59-MHz output on a 35-ns streak-camera sweep with lineout.

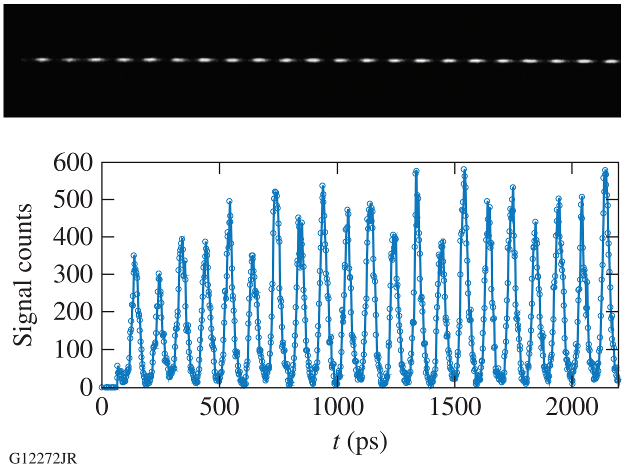

Figure 155.41
The 10.0318-GHz externally optical rate-doubled output.

Conclusion

An optically rate-doubled 5-GHz fiducal comb generator was developed with a selectable maximum 10-GHz comb repetition rate utilizing an external fiber-optic doubler. This is a self-contained and portable generator that is useful for many optical timing calibration needs. Its primary use is for ultrafast streak-camera temporal calibration. The output is fiber optic coupled at a wavelength of 680 nm (visible red) with a nearly Gaussian pulse shape. The peak output power per comb pulse is ~5 mW. The low phase noise of the internal microwave drive source provides low pulse-to-pulse jitter of less than 0.1-ps rms. An external reference frequency standard can be utilized to synchronize the output to external timing equipment. An internal reference frequency generator exists for stand-alone operation.

In the future as higher modulation bandwidth VCSEL's are developed and become commercially available, comb generators with higher rate comb outputs will be produced for enhanced timing needs. Microwave sources and drivers exist currently to support operation into the tens of GHz. It is also possible to consider incorporating the comb generator presented within a streak-camera calibration module internal to the camera itself. The remote control features of the comb generator can open up a means for developing software to perform streak-camera auto-calibration. Although the application presented focused on streak-camera calibration, these frequency-stable, low-jitter optical comb generators can also be used as timing calibrators for other diagnostic and triggering needs where fiber-optic periodic light pickets are utilized as timing fiducials.

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