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Abstract: We demonstrate supermode suppression to levels below -125 dBc/Hz and -132 dBc/Hz using Fabry-Perot etalons with finesse values of 180 and 650, respectively, for a 10 GHz harmonically mode-locked external sigma cavity semiconductor laser. The laser was hybridly mode-locked using direct electrical modulation in a compact package without the need for an external modulator.

OCIS Codes: (140.4050) Mode-locked Lasers; (320.7120) Ultrafast Phenomena

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1. Introduction

High-speed mode-locked lasers have uses in applications such as telecommunications, optical sampling, and optical signal processing where low pulse train noise is a key requirement. RMS pulse-to-pulse timing jitter is proportional to the square root of the integral of residual phase noise spectral density [1]. A roll-off is observed in mode-locked laser phase noise spectral density with a distinct corner frequency that is pushed in to lower offset frequencies with increasing cavity length for a given mode-locking frequency (harmonic mode-locking) [2, 3]. As the corner frequency is pushed in, timing jitter contribution of the region around the corner frequency decreases, however the drawback is that supermode noise spurs at cavity frequency harmonics appear. The presence of phase noise signature in supermode spurs was pointed out in [2, 4]. Achieving low residual phase noise in mode-locked lasers becomes possible by employing harmonically mode-locked long laser cavities if supermode noise spurs can be suppressed effectively. Supermode noise suppression has been demonstrated for semiconductor and fiber lasers by various methods that employ Fabry-Perot etalons (FPEs) [5-7], nonlinear Fabry-Perot filters [8], spatial hole burning [9], and two-photon absorption [10].

Supermode noise is a result of different pulses in a harmonically mode-locked laser cavity being uncorrelated in timing noise [11]. An intracavity FPE whose free spectral range (FSR) is matched to a harmonic of the cavity frequency allows the noise in each cavity pulse to be transferred to subsequent pulses, making the noise between pulses correlated. In [6], supermodes have been suppressed to levels below -130 dBc/Hz in a 10 GHz harmonically mode-locked external-cavity semiconductor ring laser using a high-finesse FPE. The gain medium was a semiconductor optical amplifier (SOA) and the laser was actively mode-locked through loss-modulation by an intracavity Mach-Zehnder intensity modulator. Here, we show results demonstrating similar levels of supermode suppression for a 10 GHz harmonically mode-locked external sigma cavity semiconductor laser using two different high-finesse FPEs (Micron Optics Fiber Fabry-Perot Filter). In this work, a 1.5 mm two-section semiconductor device is used as the gain medium and the laser is hybridly mode-locked by reverse biasing and modulating the saturable absorber section of the device. This configuration has the benefit of providing ultra-stable mode-locked pulses using direct electrical modulation in a compact package without the need for a Mach-Zehnder intensity modulator.

2. Experiment and results

Figure 1 shows the 10 GHz harmonically mode-locked external sigma cavity semiconductor laser setup. The gain section of the two-section device is biased at 65 mA. Hybrid mode-locking is obtained by applying -4 V of DC voltage and 25 dBm of 10 GHz microwave modulation to the 50 µm saturable absorber section. A 3 mm diameter ball lens collimates the beam into a fiber launcher. A sigma cavity is formed by using a polarization-diverse fiber-pigtailed circulator. The reflecting end of the cavity is the high-reflector-coated facet of the two-section device where the saturable absorber section is located. The other facet of the device is anti-reflection coated. A pellicle beamsplitter is used as an output coupler and a quarter-wave plate is used to help match the polarization state of the returning light into the gain medium. The laser output is amplified by a 2.3 mm angle-striped SOA. Faraday isolators with >40 dB isolation are used between the laser and the SOA as well as between the SOA and the fiber launcher that is used to send the SOA output to the diagnostics. In order to achieve supermode noise suppression, one of available two high-finesse fiberized FPEs was inserted in the ring section of the sigma cavity. The FPEs are made of single mode fiber and had nominal 10 GHz FSR values.

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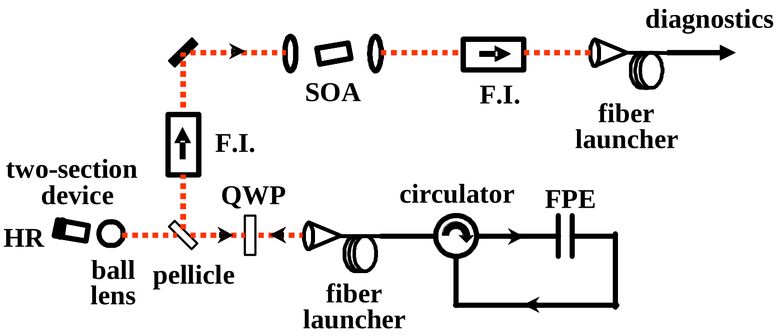

Fig. 1. Experimental setup of the 10 GHz harmonically mode-locked external sigma cavity semiconductor laser with high-finesse intracavity FPE (F.I.: Faraday isolator, HR: high reflector, QWP: quarter-wave plate, SOA: semiconductor optical amplifier).

For effective supermode suppression, the cavity frequency must match a subharmonic of the FPE FSR and the microwave drive frequency must match the FPE FSR. The cavity length is adjusted by translation of the intracavity fiber launcher. Before microwave drive is turned on, beats between cavity longitudinal modes are observed on a microwave spectrum analyzer. The microwave spectrum shows a strong beat at the FPE FSR and beats with lower power spaced from the strong beat by multiples of the cavity frequency. The lower power beats are a result of the finite finesse of the FPE that allows the oscillation of longitudinal modes around each main mode selected by the FPE. The matching of the laser cavity FSR and the FPE FSR is optimized by cavity length adjustment. The cavity length is tuned so that the low power microwave beats that have the same magnitude of frequency offset from the strong beat have the same power. The microwave drive is then turned on and its frequency is adjusted for best pulse train microwave noise characteristics.

Figure 2 displays, L(f), the single sideband residual phase noise power density spectra (out to 5 GHz offset) of the 10 GHz mode-locked laser (a) before supermode suppression as well as with supermode suppression using intracavity FPEs of finesse (b) 180 and (c) 650. The residual phase noise is measured by the phase detector method [2, 12]. Supermode noise in the sigma cavity is suppressed from about -105 dBc/Hz down to below -125 dBc/Hz with the 180 finesse FPE and below -132 dBc/Hz with the 650 finesse FPE. Note that the phase noise corner frequency of 50 kHz before supermode suppression moves out to about 160 kHz after the insertion of FPEs. The increase in the corner frequency is a result of increase in the laser cavity transmission resonance widths [3], which, in turn, is because of degradation of the cavity quality-factor due to the losses of the FPEs. These losses include the throughput loss of the FPEs and the loss due to the non-optimal spectral match of the cavity modes with the FPE modes. Throughput loss is measured to be about 8 dB and is determined by the fiber-to-fiber coupling in the FPE. Spectral match of the cavity modes to the FPE modes is optimized by the technique described above. Losses increase with increasing FPE finesse since a more stringent match is necessary between cavity modes and the FPE modes as the FPE resonances become narrower.

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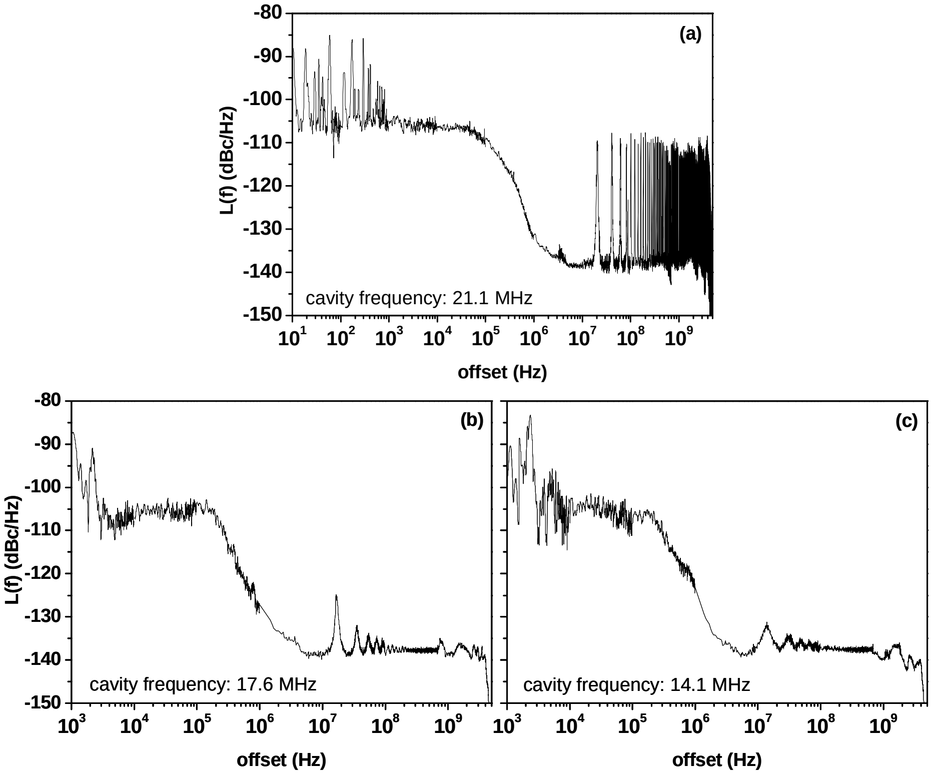

Fig. 2. Residual phase noise spectra of the 10 GHz mode-locked laser (a) without supermode suppression, (b) with an intracavity FPE of finesse 180, and (c) with an intracavity FPE of finesse 650.

Table 1 lists the RMS pulse-to-pulse timing jitter values corresponding to the residual phase noise spectra in Fig. 2. The expression

$$\Delta t = \frac{1}{2\pi f_{ML}} \left(2\int_{f_{low}}^{f_{high}} L(f)\ df \right)^{1/2}$$

was used to integrate the single noise sideband phase noise spectra. Δt is the RMS pulse-to-pulse timing jitter, f_{ML} is the mode-locking frequency, f_{low} and f_{high} are the lower and upper limits of the offset frequency range to be integrated, respectively. Pulse-to-pulse timing jitter values obtained by integrating out to the offset frequency of 10 MHz, as commonly quoted in literature, as well as out to the Nyquist offset (5 GHz) are give in the table. It should be noted that the integral of the spectrum of Fig. 2(a) out to 5 GHz offset including the supermodes is estimated by taking each supermode to contribute the same amount to the integral as the portion of the spectrum in the offset range from 10 Hz to half the cavity frequency (10.55 MHz). In other words, the integrated jitter in the 10 Hz-10.55 MHz range is multiplied by $474^{1/2}$ where 474 is the order of harmonic mode-locking [11]. As the finesse of the intracavity FPE is increased, higher supermode suppression is obtained. It was shown theoretically that the amount of supermode suppression saturates with increasing FPE finesse [7]. For the semiconductor mode-locked laser discussed here, the fact that increasing the FPE finesse from

180 to 650 gives an improvement in supermode suppression implies that the saturation region is not yet reached. As a result, higher supermode suppression ratios may be possible to achieve with higher FPE finesse values.

Table 1. RMS timing jitter values obtained from the residual phase noise spectra of Fig. 2. The lower limits of integration are the lowest offset frequencies shown in the figure (F: finesse).

upper integration limit	10 MHz	5 GHz (supermodes excluded)	5 GHz (supermodes included)
no FPE	47 fs	177 fs	1034 fs
F=180	59 fs	x	220 fs
F=650	65 fs	x	197 fs

Figure 3 shows the high-resolution (0.01 nm resolution bandwidth) optical spectrum of the 10 GHz mode-locked laser when supermode noise is suppressed with the 650 finesse intracavity FPE. For lasers built with the semiconductor device discussed above, without the FPE incorporated in the laser cavity, optical spectra obtained by the heterodyne mixing method are observed to show longitudinal modes spaced at the cavity frequency [13]. This may be attributed to the fast response time of the semiconductor gain medium (<1 ns) and the resulting switching between supermodes at a rate faster than the sweep time of practical optical spectrum analyzers (OSAs). After supermode suppression with the FPE, optical spectrum is seen to show longitudinal modes spaced at the modelocking frequency, or the FPE FSR, resulting from the oscillation of a single supermode. It should be noted that some modelocked erbium-doped fiber lasers have optical spectra with longitudinal modes spaced at the modelocking frequency [14] even without the use of intracavity FPEs. This behavior may be the result of slower (~1 ms) response time of the gain medium allowing a lasing supermode to exist for a duration longer than the sweep time of the OSA before a different supermode starts lasing at the expense of the previous one.

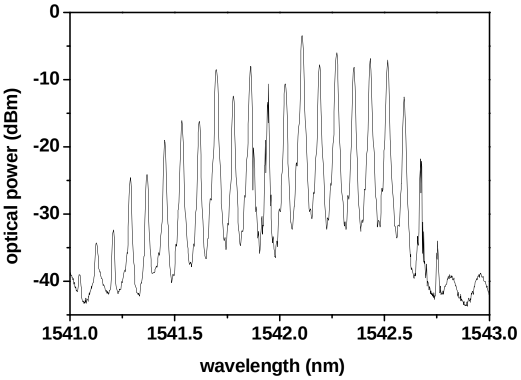

Fig. 3. Optical spectrum of the 10 GHz mode-locked sigma cavity with the intracavity 650 finesse FPE used for supermode suppression. Resolution bandwidth: 0.01 nm.

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3. Conclusion

We demonstrated supermode suppression to below -132 dBc/Hz using high finesse FPEs in a 10 GHz harmonically mode-locked external sigma cavity semiconductor laser. The two-section semiconductor gain medium enables direct modulation for modelocking without the need for an external Mach-Zehnder intensity modulator. The results show the potential of compact mode-locked semiconductor lasers as sources of ultra-stable pulse trains for use in optical sampling applications.

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