Experimental observation of excess noise in a detuned phase-modulation harmonic mode-locking laser

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The intracavity phase-modulated laser can work in two distinct stages: 1) phase mode-locking when the applied modulation frequency is equal to the cavity's fundamental frequency or one of its harmonics, and 2) the FM laser oscillation at a moderate detuned modulation frequency. In this paper, we experimentally studied the noise buildup process in the transition from FM laser oscillation to phase mode-locking in a phase-modulated laser. We found that the relaxation oscillation frequency varies with the modulation frequency detuning and the relaxation oscillation will occur twice in the transition region. Between these two relaxation oscillations, the supermode noise can be significantly enhanced, which is evidence of excess noise in laser systems. All of these results can be explained by the theory of Floquet modes in a phase-modulated laser cavity.

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A nonlinear feedback mechanism may induce an excess noise in a non-Hermitian physical system, such as the turbulence in thermosystems [1], via coupling part of the amplified perturbation back into the initial perturbation. Therefore, the perturbation experiences the strong growth repeatedly. A typical example of excess noise in nonlinear optics is actively mode-locking lasers [2–4]. Theoretical analyses show that both the amplitude modulated (AM) and frequency (phase) modulated (FM or PM) lasers have excess noise when the external driving frequency is detuned from the laser cavity's fundamental frequency or one of its harmonics. When the laser is perfectly mode locked, a few of the phase-locked modes receive extra energy from the driving signal so their thresholds for oscillation are lower than others. This results in the saturation of the gain medium so that the small perturbation from amplified spontaneous emission (ASE) gets little energy from the gain medium. Therefore, the noise level is very low compared with lasing modes. When the driving frequency has a little detuning, the signal cannot always get the lowest loss in each round trip. Then a net gain window may exist in each round trip and the perturbation from ASE can get a higher gain than the signal in this window. The noise amplification in this gain window can grow much faster than the signal. In some extreme cases, the amplified perturbation can become the new signal and replace the old one [5–7], which is called as relaxation oscillation (RO). In this article, we studied the detuning effects in a phase-modulated harmonic mode-locking fiber laser. The experimental results show that the relaxation oscillation may occur twice in the modulation frequency detuning process at different frequencies. The supermode (SM) noise can get dramatically enhanced in the frequency range between these two relaxation oscillations. It is an example of excess noise in the laser cavity. In this special case, we cannot even tell the difference between the signal and the noise in some measurements. All of these interesting phenomena only exist in detuned phase or frequency-modulated lasers, while it is unlikely to happen in an amplitude-modulated laser.

It is well known that the phase-or frequency-modulated laser can operate in two distinct states. When the modulation frequency is the same as the cavity's fundamental frequency or one of its harmonics, the laser is phase locked [8]. The laser output contains a series of short pulses in time domain and its optical spectrum has a Gaussian shape. When the modulation frequency is moderately detuned, the laser operates in FM laser oscillation [9,10]. In this case, the laser output has a constant intensity in time domain but with periodical chirp. Its optical spectrum can be very broad and follow the first-order Bessel function distribution. Almost all theoretical studies have predicted that the transition from FM laser oscillation to mode locking is sharp and excess noise may exist in this region [3,9,11]. However, no detailed experiments have been reported to study this transition process. So we set up a phase modulated fiber laser and studied how the noise grows with the modulation frequency detuning in the transition region. The setup of the fiber laser is shown in Fig. 1. To avoid the polarization change with temperature fluctuation, all fibers and components in the cavity are polarization maintained. The gain is provided by a 7 m long Erbium-doped fiber (EDF, OFS R37PM01) that is pumped by a 250 mW 1480 nm laser diode. The peak absorption of the EDF at 980 nm and 1530 nm are 9.4 dB/m and 18.1 dB/m, respectively. A 40 GHz bandwidth wave-guide-type $LiNbO_3$ electro-optical phase modulator (SOCCO, T. PM 1.5-40) is used to introduce phase perturbation in the cavity. A tunable filter with a Gaussian shape transmission

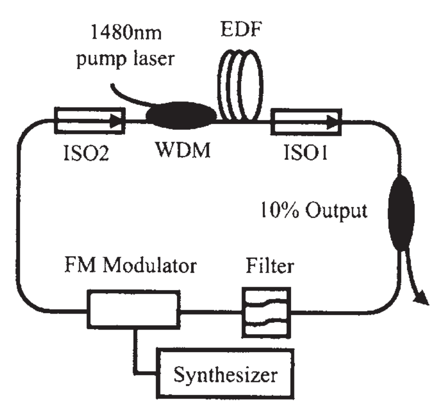

FIG. 1. The experimental setup of the phase modulated fiber laser.

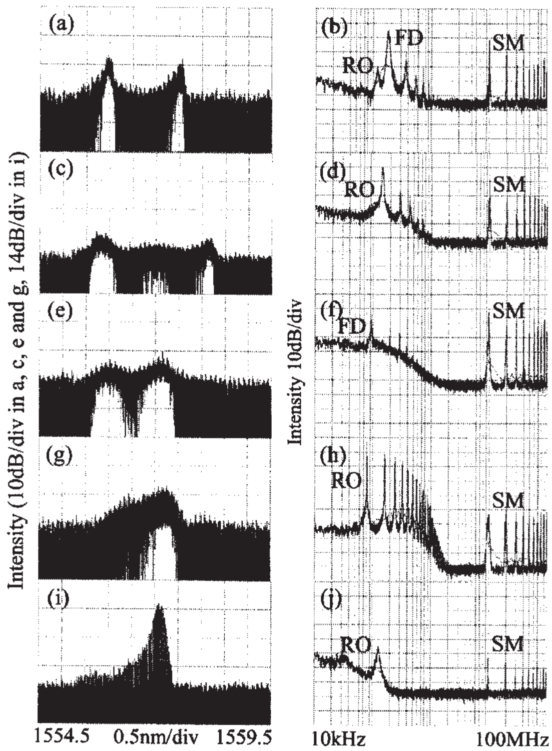

FIG. 2. The optical spectra and single sideband noise spectra when the frequency detunings are (a) and (b) 185 kHz, (c) and (d) 120 kHz, (e) and (f) 100 kHz, (g) and (h) 10 kHz, and (i) and (j) 0 Hz.

and a bandwidth of 5 nm is used to select a flat region of the amplified spontaneous emission (ASE) spectrum of the EDF, which is around 1570 nm. Two isolators are used to ensure unidirectional transmission in the ring cavity. 10% light is taken via a 9:1 output coupler for collecting the data. The laser has a fundamental cavity frequency (f_{cav}) of 9.8 MHz and the net cavity dispersion is about -0.07 ps^2. The driving signal is provided by a synthesizer (HP83640A). The modulation frequency (f_m) is around 2 GHz, which is close to the 204th harmonic of f_{cav}. We positively detuned ($f_m > 204 f_{cav}$) the fiber laser and let it work in the FM laser oscillation stage, and then we decreased f_m until it was perfectly mode locked ($f_m = 204 f_{cav}$). To measure the laser behaviors in this detuning process, we used a high-resolution (<10 MHz) optical spectrum analyzer (Aragon Photonics BOSA) for monitoring the lasing mode distribution in the optical spectrum and an electrical spectrum analyzer (Agilent E4446A) for measuring the signal converted by a high-speed photodetector with a bandwidth of 40 GHz. In general, the measurements from the electrical spectrum can give us the information of modulation even if we do not read the modulation frequency from the display of the synthesizer.

Figure 2 shows the optical spectra and single sideband noise spectra of laser operation from FM laser oscillation to phase mode locking. When the frequency detuning was greater than 130 kHz, the laser operated in FM laser oscillation. The oscillation frequencies follow a distribution of the first-order Bessel function. It means that the applied phase modulation was enhanced by the cavity mode coupling effect. With decreasing frequency detuning, the effective modulation index becomes larger and larger so the energy has the tendency to go to the optical frequencies far away from the center carrier mode [9]. The optical spectrum is dramatically broadened [Fig. 2(a)]. Based on the single sideband noise spectrum, the beatings between the modulation sidebands and the laser modes, which can be called frequency detuning (FD) noises, are the main noise source at this moment [Fig. 2(b)]. Although a small peak corresponding to the relaxation oscillation frequency also appears in the spectrum, it is hundreds of times weaker than the first-order beating between the modulation sidebands and the laser modes.

When we decreased the frequency detuning to around 120 kHz, the laser operated in the state of relaxation oscillation. The relaxation oscillation frequency and its harmonics become the main peaks in the single sideband noise spectrum [Fig. 2(d)]. Obviously the cause of this status is that the frequency detuning noise matches the relaxation oscillation frequency. The frequency detuning noise cannot be identified from the noise spectrum because it is overlapped by the peak of relaxation oscillation. Although the optical spectrum is still very wide and most energy is distributed in the two edges, we can see that part of the energy starts to move toward the carrier frequency, because the bandwidth of the gain medium (including the filter effect) distorts the enhanced phase-modulated spectrum. The energy transferred from the modulation signal cannot compensate for the loss due to the bandwidth limitation, so that part of the energy goes to the low-loss region of the gain medium, which is close to the carrier frequency [Fig. 2(c)].

As we further decreased the frequency detuning, the frequency detuning noise would move away from the relaxation oscillation frequency. Then what will occur at this moment? In our experiments, we found the supermode noise was dramatically enhanced when the modulation frequency is close to one of the harmonics of the cavity's fundamental frequency. From the optical spectrum [Fig. 2(e)], we can see that the energy around the carrier frequency became larger and larger because the loss here is small. In the single sideband noise spectrum [Fig. 2(f)], the supermode noise becomes dominant, even larger than the frequency detuning noise. In Fig. 3(a), we show the electrical spectrum around the modulation frequency. All supermode beatings have similar intensity so that it is hard to distinguish the signal corresponding to the modulation frequency. In the time domain, the trace from the oscilloscope [Fig. 3(b)] shows the pulse train with the repetition rate equal to the cavity fundamental frequency. All evidence certifies that the supermode noise dominates the laser's behavior. In this special stage, the modulation information cannot even be discovered from the measured electrum spectrum and oscilloscope trace. Hence the real signal and the noise are not distinguishable. However, we can still know the amount of frequency detuning from the single sideband noise spectrum. Because most energy is used for supporting the supermode noise, the relaxation oscillation noise is very weak so that its peak cannot be seen from the noise spectrum.

The enhanced supermode noise is maintained for a frequency detuning range of about 50 kHz. In this region, the

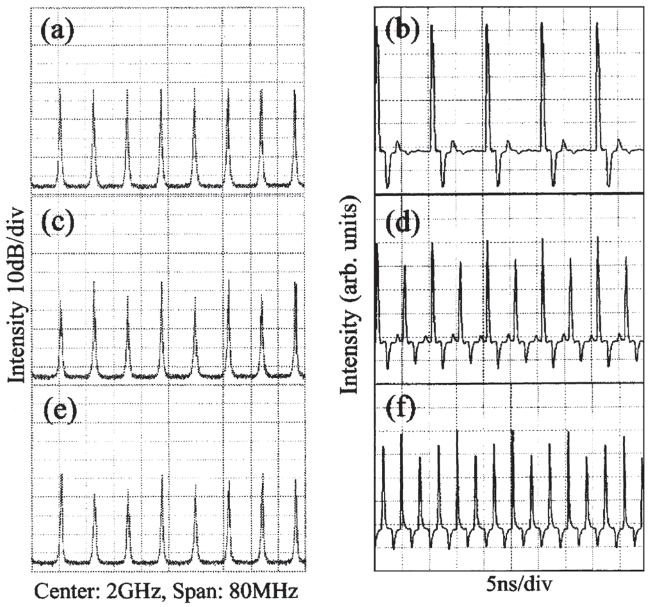

FIG. 3. The electrical spectra and the oscilloscope traces of the enhanced supermode noise with the repetition rates of (a) and (b) f_{cav}, (c) and (d) $2f_{cav}$, and (e) and (f) $3f_{cav}$.

dominant supermode beating varies with different detuned frequency, as shown in Fig. 3. In most cases, the beating corresponding to f_{cav} is the main noise. But sometimes the beating corresponding to the harmonics of f_{cav} becomes the dominant one. The harmonic order can be greater than 20 in the experiments. It's hard to find the dependence between the dominant supermode beating and the detuned frequency. Once the detuning frequency is fixed, the supermode beating is stable without external disturbance.

When the frequency detuning was decreased to around 10 kHz, the relaxation oscillation occurred again. But this time it has different properties with the previous one. First of all, as shown in the optical spectrum [Fig. 2(g)], the laser is already in the region of phase mode locking. Secondly, based on the single sideband noise spectrum [Fig. 2(h)], both the quantity of harmonics of the relaxation oscillation peak and their intensities are much greater than in the previous case. It means that the energy distributed to the noise is much higher. Thirdly, the relaxation oscillation frequency is only 80 kHz at this time, while the frequency of the previous relaxation oscillation was 120 kHz. Finally, the average output power decreases to 60% of the normal level [7], while in the last relaxation oscillation, the average output power stayed at the normal level. The noise peak corresponding to the frequency detuning noise cannot be seen in the noise spectrum because of the limitation of the scan range.

Finally, when the modulation frequency has no detuning, the laser worked in a perfect mode-locking status. The average output power returned to the normal level. The optical spectrum [Fig. 2(i)] shows clear, separated modes with the same mode spacing as the modulation frequency. From the single sideband noise spectrum [Fig. 2(j)], both the relaxation oscillation peak and the supermode noise are suppressed to a very low level. The interesting phenomenon is that the frequency of the relaxation oscillation comes back to around 120 kHz.

Now we have the complete picture of the transition from FM laser oscillation to phase mode locking. In this process, the relaxation oscillation occurs twice with different properties. The enhanced supermode noise is observed between two relaxation oscillations. If we used an amplitude modulator to replace the phase modulator in the laser cavity and repeated the experiments, the relaxation oscillation only occurred once and no supermode noise enhancement state was observed. The average output power is also stable in the whole detuning process. Therefore, the detuning effects in phase-modulated lasers are more complicated than in amplitude-modulated lasers. Then, the question is, why is this transition stage in phase-modulated lasers so complicated and what is the physics behind these phenomena?

In Refs. [3,11] based on the Floquet analysis of the laser equations in presence of a periodic phase perturbation, S. Longhi *et al.* theoretically analyzed the transition from FM laser oscillation to phase mode locking, which is induced by the intersection of two Floquet modes. The Floquet modes are not orthogonal so the laser can sustain an excess field fluctuation in the transition stage. When the laser operates in FM laser oscillation, one Floquet mode with the lowest threshold is dominant inside the cavity. In most cases, this Floquet mode is the fundamental mode and its center frequency is around the highest transmission of the gain medium. However, its threshold increases with decreasing frequency detuning due to the bandwidth limitation. When its threshold increases to a certain level, a higher order Floquet mode, which has a different center frequency, will have a lower threshold so the energy starts to transit to this mode. The threshold of the new Floquet modes decreases with decreasing frequency detuning. Therefore, both the FM laser oscillation and the phase mode locking have low thresholds but the transition stage has a high threshold. Based on the theory of relaxation oscillation, its frequency is related to the laser threshold [12]. Thus the relaxation oscillation frequency is also changed in the transition stage. By using the method in Ref. [11], we numerically simulated a phase-modulated laser system. In order to simplify the simulation, we considered the case that the modulation frequency is close to the cavity's fundamental frequency. Then the laser's threshold in the FM laser oscillation stage can be simply expressed as $g_{th}=l+D_g\Delta^2\omega_c^2\omega_m^2/(8\pi^2\omega_d^2)$, where l is the cavity loss, D_g is the filter parameter, Δ is the modulation index, ω_c, ω_m, and ω_d are the cavity's fundamental frequency, the modulation frequency, and the detuned frequency, respectively. While in the case of near-phase mode locking, the laser's threshold can be found by $(g_{th}-l)\propto(\delta T/2D_g)^2$, where δT is the time detuning between the modulation maximum and the pulse position. Strictly speaking, the Floquet modes are not the true lasing modes in the cavity, while in the simulation, we consider that the threshold of the real lasing mode have the same tendency as the Floquet modes in the transition stage, where the detuned frequency is much less than the cavity's fundamental frequency. The laser's relaxation frequency can be calculated by $\omega_{ro}=[(R-1)/\tau_a\tau_c]$, where R is the pumping rate, τ_a and τ_c are the atomic lifetime and the cavity decay time, respectively [12]. Figure 4(a) shows how the relaxation oscillation frequency changes with the frequency detuning. The relaxation oscillation frequen-

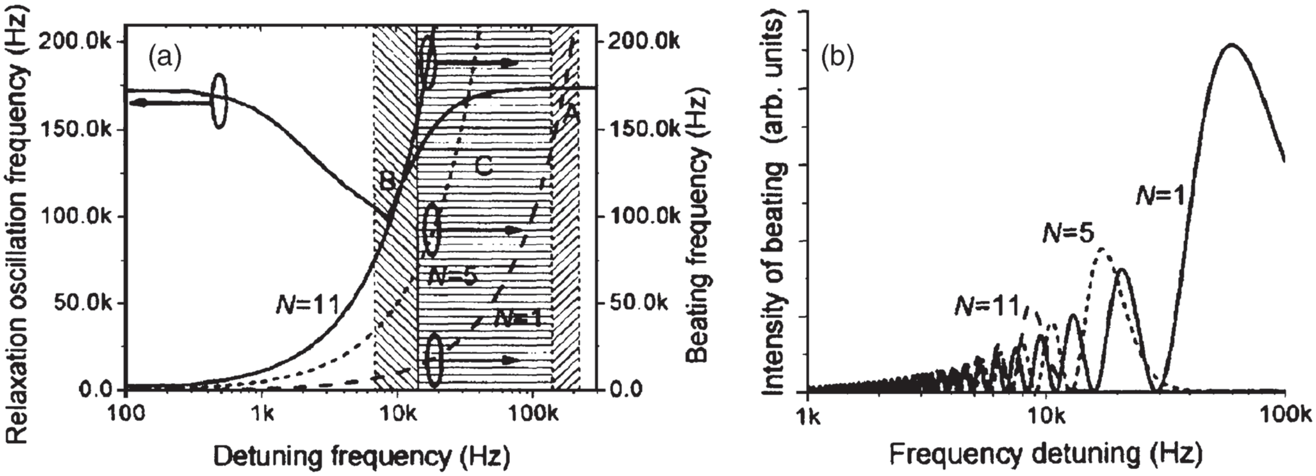

FIG. 4. The numerical simulation of (a) the relaxation oscillation frequency and beating frequencies between modulation sidebands and laser modes; (b) the intensities of beatings between modulation sidebands and laser modes. The parameters used for simulation are modulation index 0.07, cavity fundamental frequency 10 MHz, pumping rate is four times larger than normal threshold. We considered the modulation frequency is close to the cavity's fundamental frequency, the gain bandwidth is 3 GHz, which is only 1/200 of the filter bandwidth in the experiment.

cies in FM laser oscillation and phase mode locking are almost same and greater than 150 kHz, but it decreases to below 100 kHz in the transition stage. When the modulation frequency is detuned, the beatings always come from the modulation sidebands and the laser modes, which are the frequency detuning noises. In most cases, the main energy is in the first-order beating as shown in Fig. 4(b), but one of the higher order beatings may have the highest energy in some special cases. When the frequency of the beating with high energy matches the relaxation oscillation frequency, the laser will sustain the relaxation oscillation as an example of excess noise.

In Fig. 4(a), the relaxation oscillation frequency is almost constant when the frequency detuning is large, and it must have one interaction (A) with the first-order beating between the modulation sidebands and the laser modes. This is the reason behind the first relaxation oscillation in the experiments. Because the laser threshold doesn't change at this moment, the average output power is at the normal level. With decreasing of the detuned frequency, the relaxation oscillation frequency also decreases but has a different trace than with the first-order beating. Then the first relaxation oscillation will stop when its frequency separates with the first-order beating frequency. When the relaxation oscillation frequency decreases to around its lowest level (B), it may match one of the higher order beatings with the highest energy at that frequency, for instance, $N=11$ in Fig. 4(b). Hence the relaxation oscillation will occur a second time. At this moment the laser has a higher threshold than the first time so that the average output power drops. Two Floquet modes also intersect around this point and induce the great excess noise in the laser cavity. That's why the second relaxation oscillation is much more serious than the first one. When the detuned frequency continues decreasing, the relaxation oscillation frequency increases again and has no cross with any beatings with high energy in the cavity, thus the laser starts the stable-phase mode locking. Between the two relaxation oscillations [region C in Fig. 4(a)], some higher order beatings, such as $N=5$ in the simulation, can match the relaxation oscillation frequency, but they don't have the high energy at the matched frequency. Thus the relaxation oscillation cannot happen. While in region C, the laser can still support large excess of variance for field fluctuations. The supermode noise is a disturbance that can get the excess energy from the cavity because it is always naturally supported by the cavity topology. It means that almost all laser modes can oscillate at the same time. According to the amount of detuned frequency, different orders of supermode noise can dominate the laser's behavior and be maintained without any other disturbances.

In conclusion, we experimentally studied the transition from FM laser oscillation to phase mode locking by detuning the modulation frequency in a phase-modulated laser. The whole process can be described as an observed stage of the enhanced supermode noise between two relaxation oscillations. We explain these features as resulting from the excess noise in the intersection of two nonorthogonal Floquet modes, which can only occur in a detuned phase-modulated laser, while not in an amplitude-modulated laser.

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