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Cavity assisted modulation instability lasing of a fiber ring laser

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Abstract

We report on the experimental evidences of cavity assisted modulation instability (CAMI) lasing of fiber lasers. We first reviewed the theory of CAMI. We then presented experimental evidences of CAMI lasing of fiber lasers with either an anomalous or a normal dispersion cavity. It is shown that even in a fiber laser without any mode-locking element in cavity, if the orientation of the intracavity polarization controller is changed, a CW emission could be suddenly converted into a stable periodic pulse train emission. Moreover, the repetition rate of the pulse train can be adjusted over a wide range from the fundamental cavity repetition frequency to hundreds of GHz by changing the cavity detuning. We point out that the CAMI lasing should be a general effect of lasers with a nonlinear cavity.

1. Introduction

Modulation instability (MI), referred to as a process in which a continuous wave (CW) automatically breaks up into a periodic pulse train, is a general feature of wave propagation in nonlinear dispersive media that has been intensively studied in different fields. In nonlinear fiber optics, MI of light propagation in a single mode fiber was first experimentally observed by K. Tai *et al* [1]. It was interpreted as a result of interplay between self-phase modulation and anomalous fiber dispersion. Extensive studies have shown that the MI only happens in the anomalous dispersion fibers, and in particular its modulation frequency, which usually has a value of more than 100 GHz [2], is determined by the light intensity and the group velocity dispersion (GVD) of the fibers. Due to the high frequency modulation feature, it was also proposed to build MI lasing fiber lasers to generate pulse trains with ultra-high repetition rates [3-5].

M. Haelterman, S. Trillo and S. Wabnitz proposed a new type of modulation instability in a synchronously pumped fiber ring cavity [6, 7]. Different from the above conventional MI, this new MI is induced by the cavity boundary condition and can occur in both the normal and anomalous dispersion cavity regimes. Moreover, the modulation frequency of the new type of MI is not only related to the pump strength but also to the cavity detuning, measured by the total phase shift of light in one cavity roundtrip with respect to the cavity resonance. Therefore, it was also named as the cavity induced modulation instability (CIMI). S. Coen *et al* experimentally confirmed the existence of this new type of modulation instability [8].

We further extended the theory of CIMI to the case of fiber lasers [9]. We showed theoretically that a similar effect could also occur in a laser if its cavity is detuned. As a laser has an active cavity and in a steady state laser operation the laser light is always in resonance with the cavity, there are subtle differences between the features of the effect occurred in an active cavity and a passive cavity, e.g. the effect cannot self-start in a CW emission laser. To distinguish them, we have called the effect occurred in a laser as cavity assisted modulation instability (CAMI). A fiber ring laser can have high intracavity light intensity, high cavity fitness and strong cavity nonlinearity. It is an ideal system to experimentally study the CAMI. Actually Tang *et al* has reported the experimental observation of CAMI in an erbium doped fiber ring laser [9].

In this paper, we present further experimental evidences on the CAMI lasing of fiber lasers. For the sake of completeness, we have repeated the CAMI theory in section 2. Based on the theory we would like to highlight that a CW light circulating in a detuned laser cavity intrinsically suffers from CAMI. Like in the case of the conventional MI, CAMI will lead to periodical intensity modulation of the laser emission. However, different from the conventional MI, whose modulation frequency is solely determined by the light intensity and dispersion, normally has a very large value, the modulation frequency of the CAMI also varies with the cavity detuning. Through appropriately selecting the cavity detuning it is possible to change the modulation frequency of the CAMI from close zero to a very large value determined by the light intensity. In section 3 we presented our experimental results on stable periodic pulse train emission of fiber lasers with either normal or anomalous cavity dispersion. These periodic pulse trains suddenly appeared from a CW laser emission if the laser operation conditions were altered. Through modifying the laser operation conditions one could also change the pulse repetition rate of the pulse trains. Features of the observed periodic pulse train emission are found well in agreement with those theoretically predicted on CAMI. Finally, based on results of our experimental investigations, we further discussed

some other silent features of our fiber lasers that are related to CAMI. These discussions could help people to gain a better understanding on the operation of fiber lasers.

2. Theory of CAMI in a fiber ring laser

The light propagation in a fiber ring cavity is described by the extend nonlinear Schrodinger equation (NLSE) of the form

$$\frac{\partial E^n}{\partial z} = -i \frac{\beta_2}{2} \frac{\partial^2 E^n}{\partial T^2} + i\gamma |E^n|^2 E^n + gE^n \quad (1)$$

where E^n is the amplitude of the optical field in the n^{th} fiber ring cavity round-trip, β_2 is the second-order GVD coefficient, γ is the fiber's nonlinear coefficient, g is the gain coefficient of the gain fiber, z is the light propagation distance and t is the retarded time in a reference frame moving at the speed of light. Similar as the light in a synchronously pumped fiber ring cavity, the light circulation in an active fiber ring laser has to fulfill the cavity boundary condition

$$E^{n+1}(0, t) = \sqrt{\rho} E^n(L, t) \exp(i\psi_0) \quad (2)$$

where L is the length of fiber ring and ρ is the light intensity transmission rate of the output coupler in the fiber ring laser. ψ_0 is the linear phase delay of the light generated after propagating one cavity roundtrip, which is related to the optical path length of the cavity roundtrip.

Eq. (1) can be simplified to dimensionless with the following normalization: $\xi = z/L$, $U^n = \sqrt{\gamma L} E^n$, $\tau = t / \sqrt{|\beta_2| L}$, $G = gL$ and becomes

$$\frac{\partial U^n}{\partial \xi} = -i \frac{\eta}{2} \frac{\partial^2 U^n}{\partial \tau^2} + i |U^n|^2 U^n + G U^n \quad (3)$$

where η is the sign of average cavity dispersion, $\eta = \text{sgn}(\beta_2)$. Eq. (3) has the following CW solution

$$U^n = U_0 e^{G\xi} \exp\left(i \frac{U_0^2}{2G} \exp(2G\xi)\right) \quad (4)$$

where U_0 is the light intensity at the beginning of the n^{th} cavity round-trip. Following the same procedure in [8], we analyzed the stability of the CW solution under weak sideband perturbations. To this end, we add perturbation terms ν to the CW solution Eq. (4),

$$U^n = (U_0 e^{G\xi} + \nu) \exp\left(i \frac{U_0^2}{2G} \exp(2G\xi)\right) \quad (5)$$

where

$$\begin{aligned} \nu = & \nu_1^n(\xi) \exp(i\Omega\tau) + \nu_{-1}^n(\xi) \exp(-i\Omega\tau) = \exp(\mu\xi) \left[a_n \exp(i\Omega\tau) + b_n \exp(-i\Omega\tau) \right] \\ & + \exp(-\mu\xi) \left[c_n \exp(i\Omega\tau) + d_n \exp(-i\Omega\tau) \right] \end{aligned} \quad (6)$$

Take Eq. (5) back into Eq. (3) and solve ν , the eigenvalue is

$$\mu = iK = \frac{1}{2}i\Omega\sqrt{\eta^2\Omega^2 + 4\eta U_0^2} = \Omega\sqrt{-\frac{\Omega^2}{4} - \eta U_0^2} \quad (7)$$

Note that the perturbation terms also should obey the cavity boundary condition,

$$v_{\pm 1}^{n+1}(\xi = 0) = \sqrt{\rho} \exp\left[i(\psi_0 + |U_0^2|)\right] v_{\pm 1}^n(\xi = 1) \quad (8)$$

Express these relations in the terms of components $a_n, c_n, a_{n+1}, c_{n+1}$, we get

$$\begin{pmatrix} a_{n+1} \\ c_{n+1} \end{pmatrix} = \sqrt{\rho} \begin{pmatrix} \exp(iK)(\cos(\phi) + i\beta \sin(\phi)) & i \exp(-iK)(1 + \beta) \sin(\phi) \\ i \exp(iK)(\beta - 1)(-2i \sin(\phi)) & \exp(-iK)(\cos(\phi) - i\beta \sin(\phi)) \end{pmatrix} \begin{pmatrix} a_n \\ c_n \end{pmatrix} \quad (9)$$

where $\beta = \frac{\eta\Omega^2 + 2U_0^2}{-2i\mu}$ and $\phi = \psi_0 + |U_0^2|$. ϕ is the total phase delay of light propagation in one cavity roundtrip, consists of the linear phase delay ψ_0 and nonlinear phase delay $|U_0^2|$.

The eigenvalues of the matrix are

$$q_{\pm} = \sqrt{\rho} \left(p \pm \sqrt{p^2 - 1} \right) \quad (10)$$

where $p = \cos(\phi) \cosh(\mu) - \frac{\eta\Omega^2/2 + U_0^2}{\mu} \sin(\phi) \sinh(\mu)$.

CAMI will occur if the modulus of the eigenvalues is larger than unity. The gain coefficient of CAMI is defined by $G_{MI} = |q_{\pm}| - 1$. For given parameters of η and ρ , the gain spectrum is determined by the total phase delay ϕ . We define the cavity phase detuning as $\delta = \phi - 2m\pi$, where m is an integral. When the total phase delay equals multiple times of 2π , the cavity phase detuning $\delta = 0$. The laser beam is in resonance with the cavity. In the case the light propagation in the laser cavity is equivalent to that in the single mode fibers. The cavity does not introduce any influences on the light propagation. We note that in the situation if the intensity of light reaches the threshold of the conventional modulation instability, it will occur and will have exactly the same features [2]. While as far as the total phase delay is unequal to $2m\pi$, the cavity assisted modulation instability would occur. A characteristic of the CAMI is that its modulation frequency varies with the cavity phase detuning.

In Fig. 1, we compare the gain spectra under two different linear cavity phase delays for both the normal and anomalous dispersion case. It shows that through appropriately selecting the linear phase delay value, it is possible even to tune the maximum gain peak close to the zero modulation frequency. However, it is important to keep in mind that not only by changing the linear phase delay, but also by changing the nonlinear phase delay can lead to the occurrence of CAMI.

Figure. 1. The gain spectrum of CAMI under two different linear phase delays. (a) $\Psi_0=0.1\pi$, $|U_0|^2=1$, $\eta=-1$, $\rho=0.9$, (b) $\Psi_0=0.4\pi$, $|U_0|^2=1$, $\eta=-1$, $\rho=0.9$, (c) $\Psi_0=0.4\pi$, $|U_0|^2=1$, $\eta=1$, $\rho=0.9$.

Here we also would like to highlight the following point on the cavity boundary condition and CAMI of a fiber ring laser. Based on laser physics, for a laser under steady state operation its saturated gain always balances the cavity losses, so after one cavity roundtrip the light intensity returns back to its original value. Hence, in the theoretical treatment one could simply put the net gain to zero, and $\sqrt{\rho}=1$. In this case the function of the cavity boundary condition would be only to introduce a phase change on the light. When the total phase delay of the light in one cavity roundtrip is multiple of 2π , the influence of phase change introduced by the cavity boundary condition is minimum and equals zero. Otherwise, the influence of phase change would not be zero. Although under a steady state of laser operation the total phase delay of light is always in resonance with the cavity, in a real laser many external factors could result in that the cavity roundtrip phase delay deviates from multiple of 2π , e.g. by slightly tuning the intracavity polarization controller (PC) or changing the intracavity light intensity. Any of these actions could then lead to CAMI in a laser.

2. Experimental evidences of CAMI lasing

To experimentally investigate the CAMI we first constructed a fiber ring laser with a net anomalous dispersion cavity, as schematically shown in Fig. 2. The fiber ring cavity has a total length of 13.5 m, consisting of a piece of 3m Erbium doped fiber (EDF) with a normal group velocity dispersion (GVD) parameter of -48 ps/nm/km and 10.5 m single mode fiber (SMF-28) with an anomalous dispersion parameter of 18 ps/nm/km. The fiber ring cavity is estimated to have an average net anomalous dispersion parameter of 3.3 ps/nm/km. The fiber laser is pumped by a 1480 nm single mode Raman fiber laser whose maximum output power is 5 W. A polarization independent isolator is inserted in the cavity to force the unidirectional circulation of light in the cavity. Besides, an intracavity polarization controller (PC) is used to fine-tune the linear cavity birefringence. A wavelength division multiplexer (WDM) is used to couple the pumping light into the cavity, and a 10% fiber output coupler is used to output the light. The pumping coupling efficiency from the pump source to the cavity is about 60%.

All the components used in our experiment have very low polarization dependent loss (PDL) (WDM: 0.01 dB, Isolator: 0.04 dB, Coupler: 0.01 dB). Therefore, the effect of PDL induced mode locking can be excluded in our laser system [10]. The output signal is monitored with a high-speed electronic detection system consisting of 40 GHz photo-detectors and a 33 GHz bandwidth real-time oscilloscope.

Figure. 2. A schematic of the Erbium-doped fiber ring laser. EDF: Erbium-doped fiber. SMF: Single mode fiber. WDM: Wavelength division multiplexer. PC: Polarization controller. ISO: Isolator. OC: Output coupler. OSA: Optical spectrum analyser.

The CW lasing pump threshold of the laser is about 30 mW. When the pump power is increased to about 200 mW, by tuning the orientation of the intracavity PC, different states of stable periodic pulse train emission with different repetition rates can be suddenly obtained, as shown in Fig. 3.

Figure. 3. Periodic pulse train emission of the fiber laser obtained under the same pumping power but different cavity detuning. Repetition rate: (a) 107 MHz, (b) 412 MHz, (c) 1.33 GHz, (d) 2.68 GHz.

We emphasize that all these states were obtained under exactly the same cavity parameters, except that the intracavity PC orientation was changed, which stands for changing the linear cavity phase delay. Figure 4 further shows the periodic pulse trains obtained experimentally by increasing the pumping power but keeping other cavity parameters unchanged. In Table 1

we have also listed the pump power, intracavity light intensity corresponding to each of the pulse repetition rates. Starting from a stable periodic pulse train emission state, when the pump power is increased, the pulse positions in the cavity could temporally change, frequently random relative movement of the pulses could also be observed. However, after a short transient the laser emission would always settle down to another stable pulse train state with a higher repetition rate. Once a periodic pulse train state is obtained, it will remain until one deliberately destroys it. Our experimental results clearly show that the pulse repetition rate varies not only with the linear cavity detuning but also with the light intensity.

Figure. 4. Periodic pulse train emissions of the fiber laser obtained under different pumping power. Repetition rate: (a) 4 GHz, (b) 4.76 GHz, (c) 6.47 GHz, (d) 8.5 GHz.

Table 1. Relation between pumping power, intracavity light intensity and pulse repetition rate

Figure	Pumping power (dBm/W)	Intracavity light intensity (mW)	Repetition rate (GHz)
(a)	28 dBm/0.631 W	133	4
(b)	30 dBm/1 W	173	4.76
(c)	31 dBm/1.26 W	290	6.47
(d)	32 dBm/1.585 W	375	8.5

In the laser cavity there is no any mode locking element such as the saturable absorber, so no mode locking mechanism involved. Therefore, the periodic pulse trains are not a result of the harmonic mode locking. Carefully checking the time traces of the states it could be identified that there is always a weak CW background in the pulse trains, and the lower the pulse repetition rate, the more obvious is the CW background level. However, despite of the existence of the CW background the pulses were always separated equal distance in the cavity, indicating that there is a certain relationship between them. Fig. 5 shows a typical optical spectrum of these laser emission states. It exhibits a broad smooth envelop with a CW spectral spike on it. Because the pulse repetition rate is not very high, limited by the resolution (0.05 nm) of our optical spectrum analyzer (OSA), no spectral modulation caused by the periodic pulse train could be detected.

Fig. 5: A typical optical spectrum of the periodic pulse emission states shown in Fig. 3

Experimentally we found that if the pumping power is sufficiently high, coexistence of two pulse repetition rates, one with a repetition rate larger than 100GHz and the other one is only about 10GHz, could also be observed in the laser. Fig. 6 shows a case of such pulse trains obtained at a pump power of about 2 W. Fig. 6(a) shows the autocorrelation trace of the pulse train. From the autocorrelation trace, the pulse repetition rate is estimated about 250 GHz and the FWHM of the pulses is about 1.3 ps if a $sech^2$ shape pulse is assumed. Fig. 6(b) is the corresponding optical spectrum. There are strong spectral peaks on the spectrum. The interval of these strong spectral peaks is about 1.34 nm, stands for a modulation frequency of 250 GHz, which is the same as the repetition rate of the pulse train. Meanwhile, there are also some weak spikes on the spectrum. The interval of those weak spikes is about 0.1 nm, standing for a 12 GHz modulation. We interpret the formation of the high repetition rate pulse train as a result of the conventional MI lasing of the fiber laser.

Fig. 6: Pulse train emission with 250 GHz repetition rate. (a) Autocorrelation trace of the pulse train, (b) The corresponding pulse spectrum in linear scale.

In addition of fiber lasers with net anomalous cavity dispersion, we also experimentally studied fiber lasers with net normal cavity dispersion. We constructed a fiber laser with exactly the same cavity configuration as shown in Fig 2, but replaced all the SMFs by the dispersion-shifted fibers (DSFs) that have a GVD parameter of about -2 ps/nm/km. Our new

fiber cavity has a length of 23 m and an average normal dispersion parameter of about -8 ps/nm/km. Stable periodic pulse train emissions were also obtained in the fiber laser. However, in the net normal cavity dispersion regime instead of bright pulse trains, dark pulse trains were obtained. Exactly like the bright pulse trains obtained in fiber lasers with a net anomalous dispersion cavity, the pulse repetition rate of the dark pulse trains could be continuously altered through changing the intracavity PC orientation. Fig. 7 shows for example two dark pulse trains experimentally obtained under the same pump power but different intracavity PC orientations. We note again that there is no any mode-locking element in our laser cavity, and in the normal dispersion fibers there is no modulation instability neither. However, we found that in our laser as far as the intracavity light intensity is sufficiently strong, such type of stable periodic dark pulse trains could always be obtained, which clearly supports the existence of the CAMI in the normal dispersion cavity fiber lasers.

Under a relatively high pump power of about 2 W, dark pulse trains with very high repetition rate were also obtained. Fig. 8 shows the optical spectrum and autocorrelation trace of such a state. From the optical spectrum we can calculate that the modulation frequency is about 240 GHz, which coincides with the repetition rate of the pulse train shown in the autocorrelation trace. Under high pump power and also carefully tuning the PC orientation, a dark pulse train with a repetition rate of about 345 GHz was also obtained, as shown in Fig. 9. We note that previously Song *et al* reported 280 GHz dark pulse emission in a positive dispersion fiber ring laser [11]. However, how the 280 GHz dark soliton pulse train was formed in their laser was not clearly explained by the authors. Obviously, under strong pumping the CAMI could also generate ultrahigh repetition rate pulse trains.

Fig. 7: Dark pulse train emission of the fiber laser obtained under same pump power but different linear cavity detuning. (a) ~ 60 MHz pulse repetition rate, (b) ~ 170 MHz pulse repetition rate. The laser emits vector dark pulses and the two traces corresponds to the two orthogonal polarization directions of the laser emission, respectively. The pump power was fixed at ~ 1 W.

Figure 8. Dark pulse train emission with 240 GHz repetition rate. (a) The corresponding spectrum, (b) Autocorrelation trace of pulse train.

Figure 9. Dark pulse train emission with 345 GHz repetition rate. (a) The corresponding spectrum, (b) Autocorrelation trace of pulse train.

3. Discussions

Despite of the fact that under steady state operation, the phase delay of light traversing one cavity roundtrip is always in resonance with the cavity, and theoretically no CAMI should occur, our experimental results clearly show that CAMI could still occur in a fiber laser. To understand the results, we note that in a real laser cavity detuning is sensitive to the external perturbations. In our experiments either changing the orientation of the intracavity PC or the pump power could cause an initially resonant cavity to become detuned. Obviously, occurrence of the CAMI is not self-started, which is different from that of the conventional MI. Occurrence of the conventional MI is always self-started. Another difference of the CAMI from the conventional MI is that its peak gain position varies both with the cavity detuning and light intensity, while that of the conventional MI is only determined by the light intensity. Because of the differences, all the experimentally observed periodic pulse trains formed due to the conventional MI have a pulse repetition rate larger than 100 GHz, but those formed by the CAMI also have low pulse repetition rates. We note that in fiber lasers with an anomalous dispersion cavity both CAMI and the conventional MI could coexist. In particular, our experimental results show that the CAMI should have much lower threshold. At a very low pump power, we have already observed CAMI pulse trains, but only under very strong pump, coexistence of the CAMI and the conventional MI could be identified.

Like the conventional MI, the CAMI destabilizes the CW emission of a laser and causes its intensity to become periodically modulated. As in any steady-state operation of a laser the total phase delay in one cavity roundtrip must be resonant with the cavity, and pulses in the pulse train introduce nonlinear phase shifts, in a stable pulse train emission state the pulse distribution and pulse repetition rate couldn't be random. They must have a certain relationship with the cavity. We believe this could be the reason why in the steady state the pulses are always equally spaced in the cavity. The result shows that the pulses and the CW could be mutually coupled. Whenever a cavity detuning exists, each time when the light passes through the output coupler, it will interfere with the light of the previous roundtrip and lead the light intensity to fluctuate. The light intensity fluctuation will further cause the change of the nonlinear phase shift $|U_0^2|$ and so does the total phase shift. Eventually ϕ will become multiple of $2m\pi$ and the laser operation returns back to a steady state.

It is well-known that periodical light intensity modulations caused by the conventional MI will evolve into a breather structure when it propagates in a fiber [12]. However, no such

phenomenon was observed on the pulse trains caused by the CAMI in our lasers. Numerical simulations have shown that the gain bandwidth limiting could arrest the formation of breather structures. We note that Ch. Mahnke and F. Mitschke have shown that stimulated Raman scattering could convert Akhmediev breathers into soliton gas [13]. We found that the gain bandwidth limitation plays a similar role as that of the stimulated Raman scattering. Nevertheless, the existence of gain bandwidth limitation does not affect the features of the CAMI discussed in the paper.

Finally, we would like to highlight some special features of the pulses formed by the CAMI. Depending on the pump strength and the pulse repetition rate, experimentally we found that the pulses could exhibit different features. Fig. 10 shows for example a typical pulse spectral evolution with the pump power measured. At a fixed pulse repetition rate, it was observed that at the low pump power, the pulses had always broad pulse width and narrow optical spectrum (the pink curve). In this case the pulses also looked static in the cavity. No Kelly spectral sidebands were observable on the spectrum, suggesting that the pulses only have weak nonlinearity. As the pump power was increased, the pulse energy increased, pulse width narrowed down, and pulse spectrum broadened up. Eventually, Kelly spectral sidebands appeared on their pulse spectrum (the yellow and green curves). Once the Kelly sidebands were observed, the pulses also started to move in the cavity, and exhibited complicated multi-soliton dynamic features [14]. The experimental result clearly shows that before the Kelly sidebands were formed on the pulse spectrum, the pulses in the periodic pulse trains could not be an optical soliton. In fact the pulses are mutually coupled through the CW. However, as the pump power increased or the pulse repetition rate decreased, they could eventually be shaped into solitons. In this case each pulse behaves like a particle. Indeed we found that the formed solitons exhibit all the features as those of solitons obtained in the passively mode locked fiber lasers.

Fig.10: Optical spectra the pulses measured at different pump power. Pink: 200 mW; Yellow: 282 mW; Green: 316 mW.

4. Conclusions

In conclusion, we have experimentally studied the CAMI lasing of fiber ring lasers. It was shown that independent on the sign of cavity dispersion, stable periodic pulse trains could always be suddenly formed in a high power CW fiber laser if one changed the laser operation conditions. In particular, the pulse repetition rate of the formed pulse trains vary with both the cavity detuning and pump strength. We have attributed the observed phenomenon to the CAMI lasing of the fiber lasers. We have pointed out that although CAMI does not self-start in a laser operating in a steady state, as for a real laser one can easily drive its cavity away from resonance, CAMI lasing could still occur. In fiber lasers with anomalous cavity dispersion, CAMI and the conventional MI could coexist. Our experimental results have shown that the occurrence of CAMI lasing should have lower threshold than that of the conventional MI. As cavity detuning is a general effect of a laser, we expect that CAMI should be a general feature of all types of lasers.

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