A 330-W single-frequency retrievable multi-tone monolithic fiber amplifier*

Wang Xiao-Lin(王小林)†, Zhou Pu(周 朴), Leng Jin-Yong(冷进勇), Du Wen-Bo(杜文博), and Xu Xiao-Jun(许晓军)

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, *China*

(Received 30 June 2012; revised manuscript received 22 August 2012)

A single-frequency retrievable phase modulated multi-tone fiber amplifier is presented in theory and demonstrated in experiment. A multi-tone seed laser generated by a sine wave phase modulated single-frequency laser is employed for stimulated Brillouin scattering suppression in an all-fiber amplifier. A demodulation signal which is π phase shifted with respect to the modulation signal is used to retrieve the single-frequency laser from the multi-tone laser. In experiment, we first optimize the all-fiber master-oscillator power-amplifier. With this amplifier, we demonstrate a single-frequency retrievable multi-tone laser with 330-W output when driven by the multi-tone seed, while the ultimate output power is only 130 W when driven by the single-frequency laser. Then, we carry out an experiment for retrieving the single-frequency laser from the amplified multi-tone laser. Results indicate that the single-frequency laser can be retrieved with a sideband suppression of more than 20 dB. Retrieving an even higher power single-frequency laser is possible if a high power demodulator is available.

Keywords: single-frequency laser, multi-tone amplifier, phase modulation and demodulation

PACS: 42.55.Wd, 42.60.Da, 42.60.Fc **DOI:** 10.1088/1674-1056/22/4/044205

1. Introduction

High-power single-frequency fiber lasers/amplifiers are widely used in many fields, such as free space optical communication, nonlinear frequency conversion, remote sensing, and coherent beam combining.[1–6] Nevertheless, due to the restriction of thermal load, fiber damage, and nonlinear effects, especially the stimulated Brillouin scattering (SBS) effect,[7] the ultimate output power of the single-frequency fiber amplifier has been limited to the several-hundred-watt level.[1,8,9] In order to mitigate SBS and increase the output power in fiber amplifiers, various techniques for SBS suppression, including large-mode area (LMA) fibers,[10] stress,[11] thermal gradients,[12] and multi-tone drivers,[7,13] have been proposed. For the advantages of ease-of-implementation, robust performance on suppression of SBS effect, and conjunction with other SBS suppression methods, the recently proposed multi-tone driven amplifier may be one of the most attractive techniques for SBS suppression.[7] Typically, the SBS-limited output power of the N-tone amplifier will be at least N times that of a single-frequency amplifier, if the power ratio between single-frequency signals is optimized.[7]

Up to now, there have been three solutions to achieve a multi-tone single-frequency laser. The first one is to spectrally combine different single-frequency lasers using a broad band coupler.[14] The second is to build a multi-wavelength laser.[15] The third is to generate multi-tone lasers from a phase modulated single-frequency laser.[16] Of the three methods, the multi-tone laser generated from a phase modulated single-frequency laser is simplest and most compact. Moreover, with a demodulation signal, it is possible to convert the multi-tone signal back into a single-frequency signal. In previous work, Rhein *et al*.[17] have demodulated an amplified phase modulated single-frequency signal laser at a power of 10 W, which indicates that it is feasible to retrieve a single-frequency laser from a phase modulated multi-tone laser.

Combining the advantages of SBS suppression and single-frequency retrieval from the phase modulated multi-tone amplifier may lead to a feasible way for scaling-up the power of single-frequency laser passing the SBS effect limitation in a single-frequency amplifier. The above-mentioned solution can be described as fellows. First, a single-frequency laser is phase modulated by a sine wave signal to generate multi-tone laser. Then, the multi-tone laser is power amplified. As the multi-tone laser provides the ability of SBS suppression, the output power of the multi-tone amplifier will be much higher than that of a single-frequency amplifier. Finally, the amplified multi-tone laser is converted back into a single-frequency laser by using a sine wave demodulation signal. In this paper, we will study this technique in theory and in experiment. In theory, we first review the principle of SBS suppression of multi-tone amplifier, and then investigate the theory for generation/retrieve of the multi-tone laser/single-frequency by phase modulation and demodulation. In experiment, we first demonstrate a single-frequency retrievable multi-tone ampli-

*Project supported by the New Century Excellent Talents in University, Ministry of Education of China and the Scientific Research Project in National University Defense of Technology.

†Corresponding author. E-mail: wxllin@nudt.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

fier with 330-W output power. To the best of our knowledge, this is the highest power level of single-frequency retrievable multi-tone driven amplifier so far. Then we implement an experiment for retrieving single-frequency laser from the amplified multi-tone laser at a low power level. The influence on single-frequency retrieve of the four-wave mixing (FWM) is also discussed. Results indicate that in our experiment the influence of the FWM can be neglected and the single-frequency laser can be retrieved with a sideband suppression of more than 20 dB.

2. Theoretical analysis

2.1. Theory for SBS suppression of multi-tone fiber amplifier

Theoretically, multi-tone seed can increase the SBS threshold and enhance the SBS-limited output power in fiber amplifier.[7] In multi-tone driven amplifiers, not only SBS, but also FWM will appear. In this way, in N-tone driven amplifier, (N^2+N+1) optical fields (including N signals, N Stokes lights, N^2-N FWM sidebands and one pump signal) are coupled with each other through the population density and the signal/Stokes gains. The coupling of each signal results in power transfer from the Stokes wave into the signal laser.[7,13] Therefore, multi-tone driven amplifiers would increase the SBS threshold, which is predicted in theory and demonstrated in experiment.[13] Typically, the SBS-limited output power of the N-tone amplifier will be at least N times that of a single-frequency laser, if the power ratio of each signal is optimized.[7,16] In our experiment, the phase modulated single-frequency laser will provide the ability to suppress the SBS. On the other hand, the FWM may also influence the spectrum of the amplifier, thus influencing the retrieve of the single-frequency. Detail analysis will be presented after the experimental measurement.

2.2. Theory for generation/retrieve of the multi-tone/single-frequency laser

The optical signal of a single-frequency laser is

$$E(t) = E_0 \mathrm{e}^{-j\omega_0 t}. \tag{1}$$

When the signal is modulated by a sine wave phase

$$\phi_{\mathrm{m}}(t) = \psi_0 \cos(\omega_{\mathrm{m}} t), \tag{2}$$

the output optical signal is given by

$$E_{\mathrm{md}}(t) = E_0 \mathrm{e}^{-\mathrm{j}(\omega_0 t + \psi_0 \cos(\omega_{\mathrm{m}} t))}, \tag{3}$$

where ψ_0 and ω_{m} are the amplitude and angular frequency of the modulation signal, respectively. Using Bessel function, the modulated signal is written into

$$E_{\mathrm{md}}(t) = \sum_{n=-\infty}^{\infty} j^n \mathrm{J}_n(\psi_0)\, \mathrm{e}^{-\mathrm{j}(\omega_0 + n\omega_{\mathrm{m}})t}, \tag{4}$$

where $\mathrm{J}_n(\psi_0)$ is the first kind of Bessel function. We can see from Eq. (4) that due to the phase modulation, multi-tone laser with infinite sideband is generated. The frequency of each sideband is $\omega_0 + n\omega_{\mathrm{m}}$ and corresponding amplitude is $\mathrm{J}_n(\psi_0)$.

With Eq. (4), we compute the intensity of the sidebands from -15 to 15 orders when a 1064.4-nm single-frequency laser is modulated by a 100-MHz sine wave signal. Figures 1(a)–1(c) show the results when the values of modulation amplitude ψ_0 are 0.46π, 0.84π, and 1.43π rad, respectively. Results show that when different modulation amplitudes are applied, multi-tone single-frequency lasers with different numbers of tones are generated. The frequency difference between tones is equal to the modulation frequency, i.e., 100 MHz. Therefore, the sine wave phase modulated single-frequency laser is a multi-tone signal and possesses the potential ability to suppress the SBS.

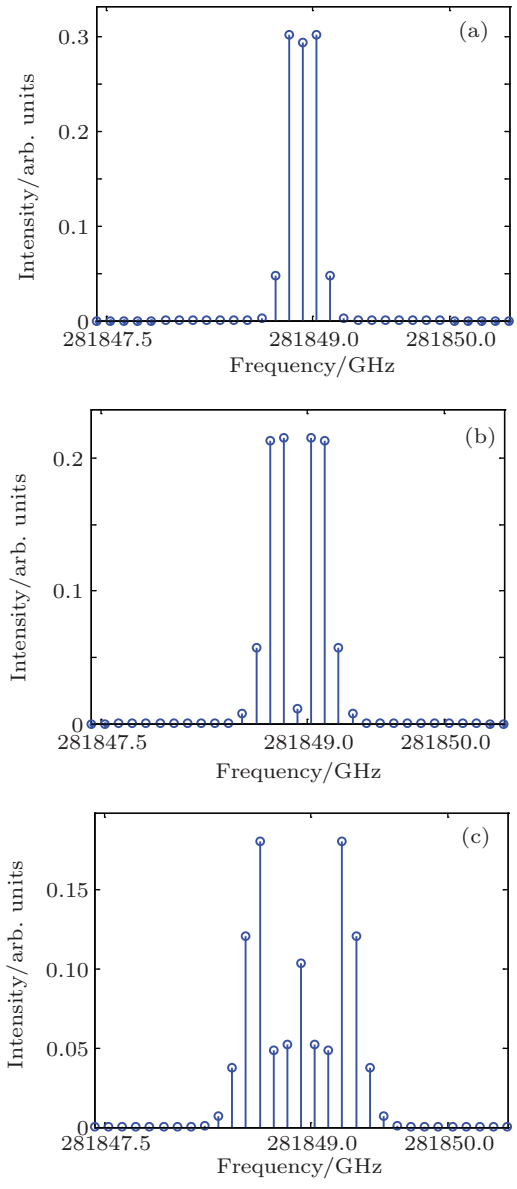


Fig. 1. (color online) Multi-tone signals generated by a phase modulated single-frequency laser with different values of amplitude $\psi_0 = 0.46\pi$ (a), 0.84π (b), and 1.43π (c).

When the phase modulated signal (in Eq. (3)) passing through a second modulator with a demodulation signal is

$$\phi_{\rm dm}(t) = \psi_0' \cos(\omega_{\rm m} t + \theta), \tag{5}$$

the resulting output signal will be

$$E_{\rm dm}(t) = E_0 \, {\rm e}^{-{\rm j}\left(\omega_0 t + \psi_0 \cos(\omega_{\rm m} t) + \psi_0' \cos(\omega_{\rm m} t + \theta)\right)}, \tag{6}$$

where ψ_0' , $\omega_{\rm m}$, and θ are the amplitude, angular frequency, and initial phase of the demodulation signal respectively. If ψ_0' is set be equal to ψ_0 and θ equals $(2n+1)\pi$, then the output demodulated signal becomes

$$E_{\rm dm}(t) = E_0 \, {\rm e}^{-{\rm j}(\omega_0 t)}. \tag{7}$$

It is clear to see that the demodulated signal is a single-frequency one with expression similar to Eq. (1). Therefore, using a demodulation signal with π phase shift with respect to the modulation signal, it is possible to retrieve the single-frequency laser from the multi-tone laser.

3. Experimental demonstration of a single-frequency retrievable multi-tone monolithic amplifier

3.1. Experimental setup

The experimental setup of the multi-tone monolithic fiber amplifier is shown in Fig. 2. The single-frequency seed laser is a commercial linearly polarized single-frequency laser generating 40 mW of power at a wavelength of 1064.4 nm with a linewidth of 87 kHz. The first phase modulator (PM1, half voltage $\sim$ 2.2 V at 50 kHz), which is driven by a function generator (FG), is used for phase modulation. When PM1 is driven by a sine wave signal with a certain amplitude, multi-tone signal will be generated. After PM1, the laser is coupled into a three-stage power amplifier chain. In the first stage amplifier (AI), a $\sim$ 1 meter long polarization maintained Yb^{3+}-doped fiber (YDF) is pumped by a 480-mW laser diode (LD). The output laser from the YDF passes through a non-polarization maintained band pass filters (BPF), an isolator (ISO) and then enters into a tap coupler. In the second stage amplifier (AII), a $\sim$ 5 m long double cladding 15 μm/130 μm (with core diameter 15 μm and inner cladding diameter 130 μm) YDF is pumped by two 9-W LDs. The output laser from the YDF passes through an isolator, a tap coupler and then enters into the main power amplifier (AIII). The main power amplifier is based on a $\sim$ 3.5-m long large-mode area (LMA) double cladding 30 μm/250 μm 0.06/0.46 NA YDF. In experiment, the LMA YDF is pumped by six 70-W level 974-nm laser diodes through a (6+1)X1 signal/pump combiner. A 0.5-m long double-clad passive fiber of the same core/inner cladding diameter and NA with the LMA YDF is spliced to the LMA YDF for power delivery. The spliced region is covered in high-index gel to strip the residual pump laser. The output end of the delivery fiber is angle cleaved at 8° to suppress spurious lasing as a result of Fresnel reflections.

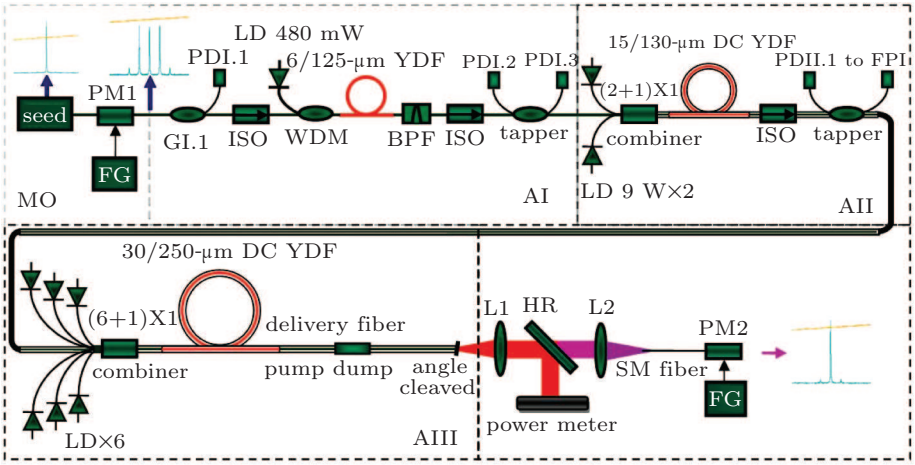


Fig. 2. (color online) Experimental setup of the single-frequency retrievable multi-tone amplifier. MO: master oscillator, FG: function generator, PM1, PM2: phase modulator, CI.1: coupler, ISO: isolator, LD: laser diode, WDM: wavelength division multiplexer. YDF: Yb^{3+}-doped fiber, PDI.1, PDI.2, PDI.3, and PDII.1: photodetector; tapper: tap coupler. L1, L2, lens; HR: high reflector.

In Fig. 2, tap couplers between amplifiers are used to monitor the output power in the current stage amplifier and the backward power in the next stage amplifier. For example, in AII, PDII.1 is used to monitor the power of the backward light (especial the SBS) of the main power amplifier (AIII). When the power detected by PDII.1 is more than 0.15 mW (which means that the total power of the backward light in the tap coupler is $\sim$ 150 mW), the power supply of the pumps in main amplifier will be cut off automatically by a special designed control circuit. This will avoid unwanted damages to the for-

mer stage amplifier. Therefore, when the monitored SBS is ~ 150 mW, the corresponding output power in the amplifier is considered to be the SBS-limited one. In AII, about 0.1% of the total output power tapped by another port of the tap coupler is used for spectrum measurement and single-frequency retrieve. The laser from the main power amplifier is first collimated by a lens (L1) and then sampled by a high reflector (HR). The main power of the reflection beam is sent to a power meter, the transmission light which contains less than 1% of power is focused by a lens (L2). After L2, the focused light is coupled into a single-mode (SM) passive fiber. The laser collected in the SM fiber is first sent into a phase modulator (PM2) and then coupled into an F-P interferometer (FPI). The measured signal from the FPI will be recorded by an oscilloscope.

3.2. High power multi-tone driven monolithic amplifier

In experiment, the single-frequency laser is phase modulated by a sine wave signal with an amplitude of 0.84π and a frequency of 100 MHz (i.e., $\phi_{\rm m}(t) = 0.84\pi\cos(2\pi \times 10^6 t)$). Then, multi-tone laser is generated and used for power amplification. We first study the SBS suppression and compare the output power characteristic when the amplifier chain was seeded by the multi-tone laser with that by the single-frequency laser. The results are shown in Fig. 3. In Fig. 3(a), when the amplifier chain is driven by single-frequency laser, the monitored backward power in the tap coupler starts to increase linearly up to an output power of about 115 W. The nonlinear increasing of the backward power is observed when the output power is higher than 126 W. When the output power is about 130 W, the total monitored backward power in the tap coupler is ~ 133 mW. Thus, the SBS-limited output of the single-frequency driven amplifier is about 130 W. When the amplifier is driven by the multi-tone amplifier, the output power of the amplifier reaches 330 W at the limited pump power of about 400 W, with an efficiency of more than 82% as shown in Fig. 3(b). The maximum monitored backward power is about 123 mW, the nonlinear increasing of the backward power is not observed even at the highest output power. One can see that the maximum backward power in the multi-tone amplifier is close to that in a single-frequency amplifier. This is because the backward light contains not only SBS light, but also the reflected light from the output ends of the amplifier, when the output power increases, the backward power thus increases correspondingly. Therefore, it could be concluded that the output power in the multi-tone driven amplifier is limited by the pump power instead of the SBS effect. Comparing Fig. 3(a) and Fig. 3(b), the results indicate that in the multi-tone amplifier, the output power is more than 2.5 times that in a single-frequency amplifier. Note that the SBS threshold for an N-tone laser could be more than N times that of a single frequency laser,[16] the output power of the four-tone amplifier could be further increased by increasing the pump power. In experiment, we take measures such as coiling the YDF, water-cooling of the YDF, and stripping of the power in the outer cladding so as to make the main amplifier work in the lower mode. The measured M^2 is about 1.3 in both directions.

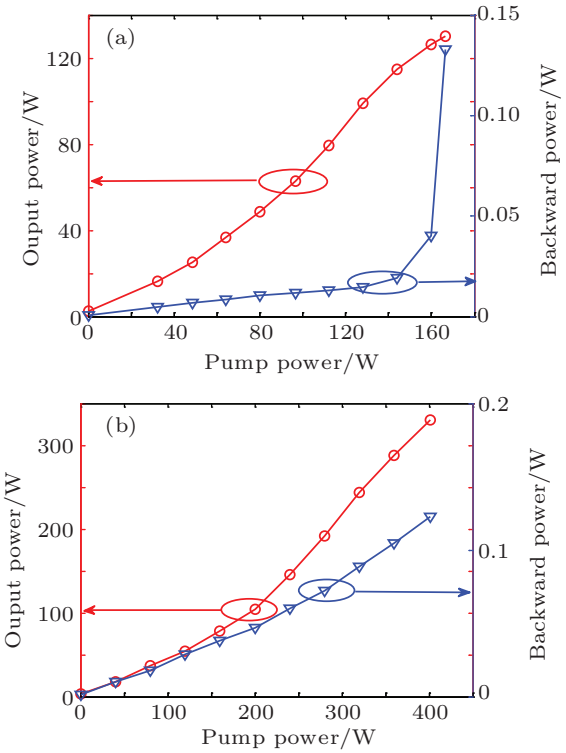


Fig. 3. (color online) Curves of output power and backward power versus pump power when driven by a single-frequency laser (a) without and (b) with phase modulation. Modulation signal is $\phi_{\rm m}(t) = 0.84\pi\cos(2\pi \times 10^6 t)$.

Then, the spectrum of the power amplifier was also captured by an optical spectrum analyzer with a resolution of 0.5 nm. The result is shown in Fig. 4(a). It can be seen that the amplified spontaneous emission (ASE) is suppressed by ~ 30 dB, and the residual pump power is 25 dB less than that of the signal power.

In order to study the details of the spectrum, we measure the spectrum both in the seed laser and from the amplifier by the FPI. Firstly, we measure the spectra of the seed laser with and without phase modulation as shown in the dash–dotted curve in Fig. 4(b), respectively. The curve linearly increasing across the graphs is the scan voltage applied to the FPI. Comparing Fig. 4(b) with Fig. 1(b), we can conclude that experimental result is in agreement with the theoretical one. In order to measure the spectrum of the amplifier, the laser from the amplifier is coupled into the SM fiber and sent into the FPI (see Fig. 2). The recorded signal is shown in Fig. 4(c). Comparing Fig. 4(c) with Fig. 4(b), we can see that there is no remarkable difference between the spectrum of the seed laser and that from main amplifier. The reason is that the power of the FWM sidebands is so small that the FPI response voltage is smaller than the resolution of the oscillator. Therefore, FWM

sidebands cannot be recorded efficiently by the oscilloscope. This will be confirmed theoretically later.

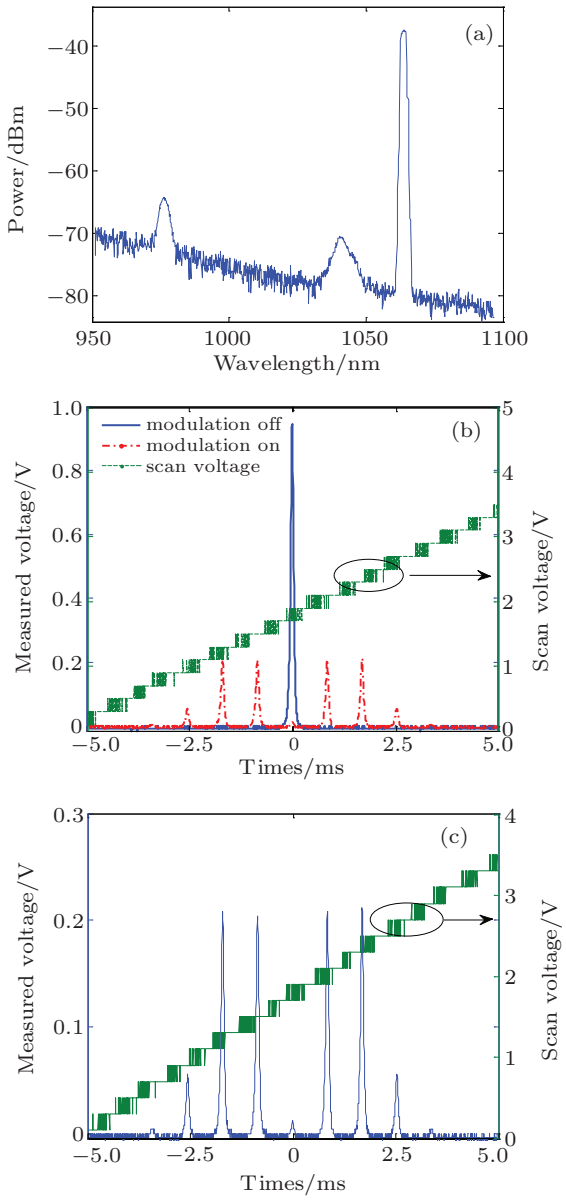


Fig. 4. (color online) Spectra of a multi-tone driven amplifier measured by an OSA (a) and an FPI (b) at the output power of 330 W. (c) Oscilloscope trace of the FPI measured spectrum when the modulation signal is on and off.

3.3. Theoretical analysis of the FWM sidebands in the experiment

As the FWM may change the spectral shape of the amplified laser, thereby influencing the performance of the single-frequency laser retrieval, it is necessary to estimate the power level of each FWM sideband in the amplifier theoretically.

In theory, the power of the FWM sideband produced by pump laser and signal laser can be calculated by[18–20]

$$P_{\mathrm{PPS}} = \eta\gamma^2 P_{\mathrm{s}} P_{\mathrm{p}}^2 L_{\mathrm{eff}}^2. \tag{8}$$

The frequency of the sideband is $\omega_{\mathrm{pps}} = 2\omega_{\mathrm{p}} - \omega_{\mathrm{s}}$, ω_{p} and ω_{s} are the frequency of the pump and signal laser, respectively.

In Eq. (8), η is the conversion efficiency; for a signal positioned close to the pump in fiber amplifier, $\eta = 1$;[19] P_{p} and P_{s} are the powers of pump and signal laser with frequency of ω_{p} and ω_{s}, respectively; γ is the nonlinear parameter, it can be calculated as $\gamma = n_2\omega/(cA_{\mathrm{eff}}) = 2\pi n_2/(\lambda A_{\mathrm{eff}})$.[21] with n_2 being the nonlinear index coefficient, λ being the wavelength of the laser and A_{eff} being the effective core area of the fiber;[21] L_{eff} is the effective interaction length.[21]

For a silica-based fiber, $n_2 = 3\times10^{-20}$ m^2/W at a wavelength of 1.064 μm.[21] Consider the parameters in our experiment (the core diameter of the fiber is 30 μm, and laser wavelength is 1.064 μm), then γ will be calculated to be $\gamma = 2.5\times10^{-4}$ m$^{-1}\cdot$W^{-1}. In experiment, there is 3.5-m active fiber that deliveries a non-uniform power and a 0.5-m passive fiber deliveries a power up to 330 W. The effective interaction length at a full power of 330 W can be estimated to be 1 m. Therefore, the power of the FWM sidebands is

$$P_{\mathrm{PPS}} = 6.3\times10^{-8} P_{\mathrm{s}} P_{\mathrm{p}}^2. \tag{9}$$

In experiment, there are 9 sidebands in the seed laser spectrum [see Fig. 4(b)]. After the main power amplifier, we assume that all the power is included in the sidebands in Fig. 4(b). Consider the fact that the total power of the laser in the main amplifier is 330 W, then the powers at different frequencies will be estimated to be 2.3 W, 18.5 W, 71.2 W, 71.2 W, 3.5 W, 71.2 W, 71.2 W, 18.5 W, and 2.3 W. Here, for simplicity, we assume that four of the highest signals are equal. Using these powers and Eq. (9), we calculate the power of the FWM sidebands, and the results are shown in Fig. 5. There are 25 sidebands in the output of the laser. The total power of the 25 sidebands is 0.68 W, which is 0.21% of the total power from the amplifier. The highest power of those FWM sidebands is less than 0.1 W (0.0936 W) at the central frequency. Compared with the influence of the power of 3.5 W at the center frequency, the influence of the power can be neglected.

Now we calculate the voltage response of the FWM sidebands in the FPI. The response voltage of the FWM sidebands is calculated by $V_{\mathrm{FWM}} = P_{\mathrm{FWM}} \times V_{\mathrm{max}}/P_{\mathrm{max}}$, where V_{max} is the maximum voltage that the FPI responds, P_{max} is the highest power in the values at all the frequencies and P_{FWM} is the power of the FWM sidebands. In experiment, the laser power (from the main power amplifier) coupled into the FPI is so small that the amplifier (after the photodetector) works at the full gain. In this case, $V_{\mathrm{max}} = 0.212$ V, which is corresponding to a maximum power of $P_{\mathrm{max}} = 71.3$ W. From Fig. 5, the maximum power P_{FWM} is 0.0936 W, then $V_{\mathrm{FWM}} = 2.7831\times10^{-4}$ V. From Fig. 4(b), we can see that the noise voltage is $V_n = 0.004$ V. Compared with V_n, the maximum response voltage of the FWM sideband is small. Therefore, it is difficult to distinguish FWM sidebands. This accords with the experimental result.

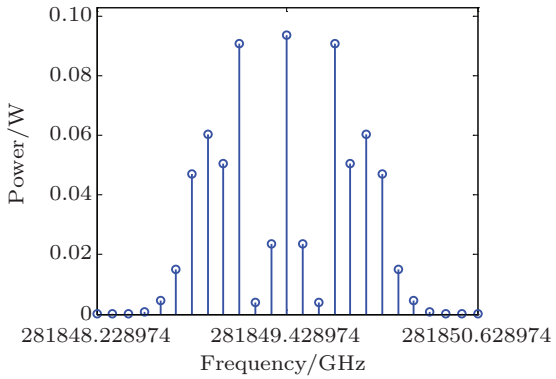


Fig. 5. (color online) Power distribution of the calculated FWM sidebands.

In brief, there are really FWM sidebands in the amplifier, but they cannot be recorded effectively by the FPI and the oscilloscope. The reason is that the power of the FWM sidebands is so small that the FPI response voltage is less than the resolution of the oscilloscope. Therefore, we can conclude that the FWM sidebands have little influence on the spectrum of the amplifier as well as the retrieved single-frequency signal.

3.4. Experiment for retrieving a single-frequency laser from the multi-tone laser

In experiment, when PM2 is driven by a sine wave signal $\phi_{\rm dm}(t) = 0.84\pi\cos(2\pi \times 10^6 t + \pi)$ (which is π phase shifted with respect to the modulation signal), the demodulated signal is recorded and shown in Fig. 6(a). A fine scale measurement is also shown in Fig. 6(b). Most of the modulated sidebands are removed, only two sidebands near the central frequency are recorded compared with the scenario Fig. 4(c). The powers of both sidebands are calculated to be 20.9 dB less than that of the signal. The residual error is mainly caused by the differences in frequency, amplitude, biasing voltage, and phase between the modulation signal and demodulation signal. Because the FWM sidebands is very small, there is no evident influence on the single-frequency retrieval.

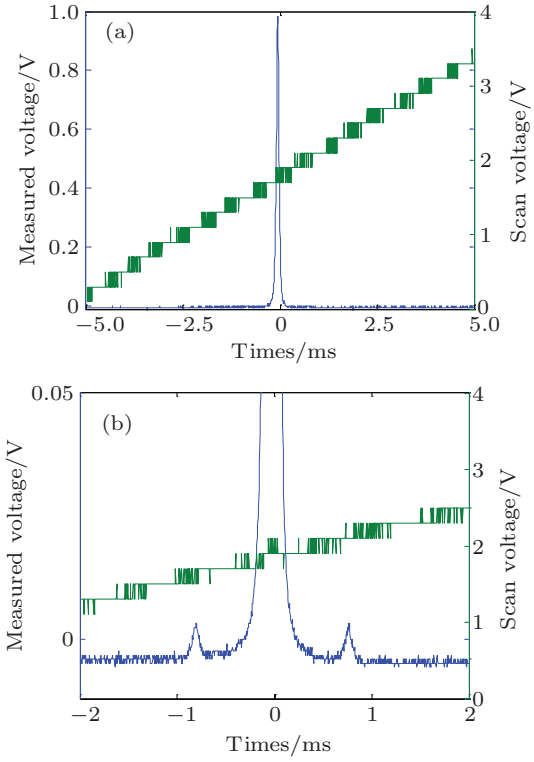


Fig. 6. (color online) Demodulated optical signals (a) in large scale and (b) in fine scale.

4. Discussion of power scaling for the multi-tone amplifier in experiment

In a high power multi-tone amplifier, not only for FWM, but also for SBS, stimulated Raman scattering (SRS) will also limit the power of the amplifier. Here, we will estimate the power scaling with taking into account the SBS, SRS, and FWM effects, respectively.

In a multi-tone amplifier, if the power in one of the tones exceeds the SBS threshold $P_{\rm th}$ of the single-frequency laser, SBS will appear. When the power of the maximum tone is $P_{\rm th}$, the maximum power is $P_{\rm th}/\alpha$, where α is power ratio of the maximum tone to the overall power including all tones. In experiment, SBS appears when the single-frequency laser is 126 W. α is calculated to be 0.2158, then the calculated total power is 583 W. Therefore, the SBS limited power is about 583 W in our experiment.

For the SRS effect, the threshold power can be estimated by $P_{\rm th} = 16A_{\rm eff}/g_{\rm R}L_{\rm eff}$.[21] In experiment, $A_{\rm eff}$ is calculated to be 7.0×10^{-10} m^2 and $L_{\rm eff}$ is estimated to be 1 m. For a silica-based fiber, $g_{\rm R} = 1 \times 10^{-13}$ m/W. Therefore, the SRS limited power is calculated to be 113 kW.

For the FWM effect, we suppose that the threshold appears when the power of the maximum FWM sideband is 10% of the minimum signal tone power. Therefore, we have $0.1P_{\rm min} = 0.1\beta P_{\rm max} = 6.3 \times 10^{-8} P_{\rm max1} P_{\rm max}^2$, $P_{\rm th} = P_{\rm max}/\alpha$. Here β is the power ratio of the minimum tone to maximum tone. From our experimental power distribution in Fig. 3, we have $\beta = 0.032$, $\alpha = 0.2158$, and $P_{\rm max1} = P_{\rm max}$. Then $0.1 \times 0.032 \times P_{\rm max} = 6.3 \times 10^{-8} P_{\rm max}^3$, where $P_{\rm max} = 225.37$ W and $P_{\rm th} = 1044$ W. Therefore, the FWM limited power is about 1044 W.

The maximum power of the amplifier can scale up to 583 W. This power is similar to that one estimated by N times the power of the single-frequency laser. Moreover, if the number of the tone increases, the output power will increase.

It should be noted that we have not retrieved a single-frequency laser at a high power level, because the damage threshold of the available phase modulator is less than 100 mW. Up to now, the damage threshold of a commercially available free space KTP phase modulator is 20 W/mm^2,[22] the power handling ability of this type of phase modulator is

about 60 W. Although high power (up to 500 W) phase modulators are not available yet, with the development of material and relative technology such as resonant phase modulators,[22] we believe that high threshold, high bandwidth, and relatively low half-wave voltage phase modulators will be available in the future.

5. Summary

In this paper, a single-frequency retrievable multi-tone amplifier is presented in theory and demonstrated in experiment. In theory, we first review the principle of SBS suppression of a multi-tone driven amplifier, and then investigate the theory for generation/retrieval of the multi-tone laser/single-frequency laser by phase modulation and demodulation. In experiment, we first demonstrate a multi-tone amplifier of 330-W output with single-frequency retrieve ability. The power of the multi-tone amplifier is more than 2.5 times the value of the single-frequency amplifier. To the best of our knowledge, this is the highest power demonstration of a single-frequency retrievable multi-tone driven amplifier. Then, we implement an experiment for retrieving a single-frequency laser from the multi-tone amplifier at a low power level. Results indicate that the single-frequency laser can be retrieved with a sideband suppression of more than 20 dB. The power of the retrieved single-frequency laser beam is restricted by the available high power phase demodulator. Note that the power of the amplifier in our experiment can scale up to 580 W by adding pump power. In this way, a single-frequency laser with more than 500-W output power could be retrieved if a high power low loss demodulator is available. Moreover, consider that there are seven remarkable sidebands in Fig. 4(b), then the linewidth of the laser will be roughly computed to be 600 MHz. The corresponding coherence length of the laser is about 0.5 m, while for a broad band signal the coherence length is small (usually less than 0.03 m),[23] which is easy to be controlled in coherent combining. Therefore, even if without phase demodulation, this type of multi-tone amplifier can be used for coherent beam combination without needing any strict optical path control.

Acknowledgment

The authors are grateful to Hu Xiao for support, and also to Han Kai for the experiment.

References

[1] Gray S, Liu A, Walton D T, Wang J, Li M, Chen X, Boh A R, Demeritt J A and Zenteno L A 2007 *Opt. Express* **15** 17044
[2] Li J, Duan K, Wang Y, Zhao W, Zhu J and Guo Y 2008 *IEEE Photon. Tech. Lett.* **20** 888
[3] Wang X L, Zhou P, Ma Y X, Ma H, Xu X J, Liu Z J and Zhao Y 2010 *Chin. Phys. B* **19** 094201
[4] Xue Y H, He B, Zhou J, Li Z, Fan Y Y, Qi Y F, Liu C, Yuan Z, Zhang H and Lou Q H 2011 *Chin. Phys. Lett.* **28** 054211
[5] Jianfeng L and Jackson S D 2011 *Chin. Phys. B* **20** 034201
[6] Wang X L, Ma Y X, Zhou P, He B, Xue Y H, Liu C, Li Z, Xiao H, Xu X J, Zhou J, Liu Z J and ZhaoY J 2011 *Chin. Phys. B* **20** 114201
[7] Dajani I, Zeringue C and Shay T 2009 *IEEE J. Sel. Top. Quantum Electron* **15** 406
[8] Zeringue C, Vergien C and Dajani I 2011 *Opt. Lett.* **36** 618
[9] Xiao H, Dong X L, Zhou P, Xu X J and Zhao G M 2012 *Chin. Phys. B* **21** 034201
[10] Leigh M, Shi W, Zong J, Yao Z, Jiang S and Peyghambarian N 2008 *Appl. Phys. Lett.* **92** 181108
[11] Brown D C and Hoffman H J 2001 *IEEE J. Quantum Electron.* **37** 207
[12] Liu A P 2007 *Opt. Express* **15** 977
[13] Weßels P, Adel P, Auerbach M, Wandt D and Fallnich C 2004 *Opt. Express* **12** 4443
[14] Wang X L, Leng J Y, Xiao H, Ma Y X, Zhou P, Du W B, Xu X J, Liu Z J and Zhao Y J 2011 *Opt. Lett.* **36** 1338
[15] Zhang Z, Wu J, Xu K, Hong X and Lin J 2009 *Opt. Express* **17** 17200
[16] Liu Y, Lü Z, Dong Y and Li Q 2009 *Chin. Opt. Lett.* **7** 29
[17] Rhein S, Schmidt O, Zimer H, Schreiber T, Eberhardt R and Tünnermann A 2011 *Proc. SPIE* **7914** 1
[18] Hill K O, Johnson D C, Kawasaki B S and Macdonald R I 1978 *J. Appl. Phys.* **49** 5098
[19] Brès C, Zlatanovic S, Wiberg A O J and Radic S 2011 *Opt. Express* **19** B621
[20] Shibata N, Braun R and Waarts R 1987 *IEEE J. Quantum Electron.* **23** 1205
[21] Agrawal G P 2005 *Nonlinear Fiber Optics* (Beijing: Beijing World Publishing Corporation) p. 367
[22] Newport Inc. DC-250 MHz Electro–Optic Phase Modulators [EB/OL]. 2007 http://search.newport.com/?q=*&x2=sku&q2=4063-M
[23] Yu C X, Augst S J, Redmond S M, Goldizen K C, Murphy D V, Sanchez A and Fan T Y 2011 *Opt. Lett.* **36** 2686