

# Yb band parasitic lasing suppression in Er/Yb-co-doped pulsed fiber amplifier based on all-solid photonic bandgap fiber

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Received: 3 May 2013 / Accepted: 22 June 2013 / Published online: 19 July 2013  
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**Abstract** A novel kind of all-solid photonic bandgap fiber (AS-PBGF) has been used in the master oscillator power amplifier structured Er/Yb-co-doped pulsed fiber amplifier to suppress the Yb band parasitic lasing for the power scaling and safety operation. To the best of our knowledge, this is the first time to report the use of AS-PBGF to suppress the Yb band parasitic lasing. The experimental results show that the Yb band parasitic lasing has been suppressed efficiently and the amplifier power has been raised dramatically with the utilization of AS-PBGF. An output power of 2.66 W was finally obtained without any unwanted parasitic lasing.

## 1 Introduction

During recent decades, the fiber laser operating at the eye-safe wavelength of 1,550 nm has been highly welcomed for many applications, such as optical communications, range finding and laser radar. However, the output power has been limited by the ion-clustering of Er<sup>3+</sup> ions in purely Er-doped fiber [1] and the Yb amplified spontaneous emission (Yb-ASE) in Er/Yb-co-doped fiber [2]. Moreover, in the Er/Yb-co-doped fiber systems, the parasitic lasing

and self-pulsing effects will occur inside of the fiber with the increase in pump power, which can easily damage the system [3].

To increase the output power of Er/Yb-co-doped fiber lasers, the Yb-ASE should be controlled. Several approaches have been made to handle the Yb-ASE. In Ref. [3] two fiber Bragg gratings (FBG) and a specially designed wide-band filter were utilized to filter out the Yb-ASE, this solution being effective but at the same time-costly and time-consuming for tailor-made FBGs. Another approach was using the counter-propagating pumping scheme [4], but the Yb-ASE can still appear under high-power operation. Meanwhile, the standard tapered fiber bundle (TFB) couplers are not suitable for long-term operation for counter-pumping scheme because their low core-to-cladding isolation can lead to low damage threshold. The short-wavelength cutoff property of photonic bandgap fibers was also used to suppress the Yb-ASE and parasitic lasing [5]. But, the amplification efficiency is very low due to the scattering loss in the core of the present Er/Yb-co-doped photonic bandgap fiber.

In 2007, Jeong and his associates proposed that an Er/Yb-co-doped fiber laser could be scaled to higher power levels around the wavelength of 1.5 μm, when a controlled simultaneous laser oscillation at 1.0 μm rather than a suppression of such a laser oscillation was utilized [6]. Based on this idea, several approaches have been proposed to control the Yb-ASE. An auxiliary signal at 1,064 nm was used to ensure stable amplifier operation [7]. The influences of the wavelength of auxiliary signal external-cavity laser on amplification and reabsorption were also explored experimentally [8] and theoretically [9, 10]. This method is efficient and elegant; however, it needs another laser source operating in ~1.0 μm and relevant fiber isolators for all fiber configurations. Moreover, the slope

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efficiency of the signal was not increased obviously although the presence of 1,064 nm seed prevents parasitic lasing and provides stable amplifier operation. For this consideration, a positive feedback loop for the 1  $\mu\text{m}$  in the amplifier was provided to control the 1  $\mu\text{m}$  emission in the Er/Yb-co-doped fiber amplifier [11, 12]. This loop forms a ring resonator inside an amplifier, and the positive feedback induces stable and controllable lasing around 1,060 nm. This approach also has its own drawbacks that it needs another ring resonator and the configuration is more complex. Furthermore, the slope efficiency at 1,550 nm would be affected by the wavelengths of the auxiliary seed or the Yb band stimulating lasing in the positive feedback loop. All of the approaches mentioned above are operating in continuous wave; the effectiveness of these methods is not confirmed in the pulsed lasers.

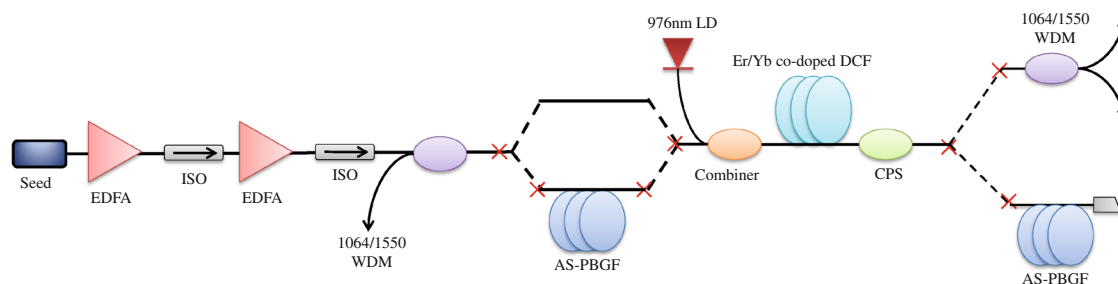
In our works, we present a novel method to avoid the Yb band parasitic lasing using an all-solid photonic bandgap fiber (AS-PBGF) with a bandgap at 1,030–1,140 nm for the first time to our knowledge. In our previous works, a kind of AS-PBGF was fabricated for Yb-ASE controllable filtering [13]. Here, we introduce two pieces of such AS-PBGFs at the two ends of active Er/Yb-co-doped double-cladding fiber to attenuate the forward and backward Yb-ASE to increase the threshold of parasitic lasing. A 1,550-nm nanosecond seed has been amplified to 2.66 W using this approach. The experimental results have shown that the Yb band parasitic lasing has been suppressed effectively. The threshold of parasitic lasing as well as the power level for the stable and safe operation has been raised dramatically.

## 2 Experimental setup

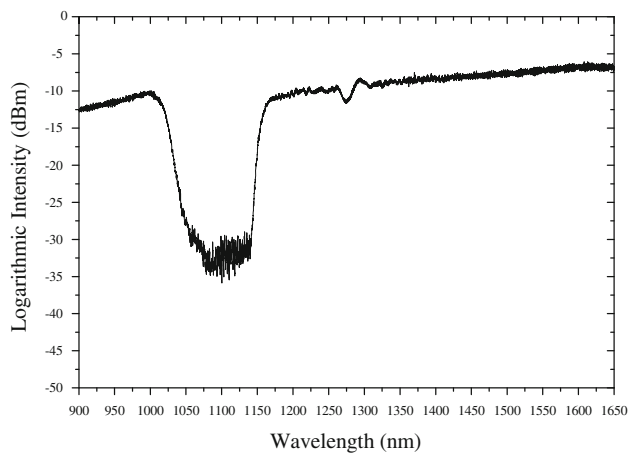
The experimental setup of Er/Yb-co-doped fiber amplifier is demonstrated in Fig. 1. It is a MOPA structure consisting of a seed laser and three amplifier stages. The seed source is a nanosecond pulsed fiber laser which has a modulated pulse duration about 100 ns with repetition frequency of 200 kHz. The first two stages (preamplifier) are Er-doped

fiber amplifiers (EDFA). Both of them are based on 20-m-long, single-mode Er-doped fiber (Nufern EDFC-980-HA) and pumped by a 976-nm, single-mode diode laser with a maximum output power of 550 mW. Through two-stage preamplifiers, the power of seed laser ( $\sim 10$  mW) has been amplified to 201 mW to feed the third stage (power amplifier stage). The third stage (power amplifier) is an Er/Yb-co-doped fiber amplifier based on a 5.8-m-long Er/Yb-co-doped double-cladding fiber (DCF, Nufren SM-EYDF-6/125-HE) with a core diameter of 6  $\mu\text{m}$  and inner cladding diameter of 125  $\mu\text{m}$  and forward-pumped by a 20 W multimode laser diode (LD) through a commercial tapered fiber bundle (TFB) combiner (pump efficiency is 95 %, and signal insert loss is 0.19 dB). The unabsorbed pump light from the power amplifier stage is rejected by a cladding power stripper (CPS). Each stage is separated with an isolator (ISO) that protects the prior-stage from backscattered light. Before the third stage, a 1,064/1,550-nm-wavelength division multiplexer (WDM) coupler (the insertion loss is 0.07 dB @ 1,550 nm, 0.13 dB @ 1,064 nm) is used to monitor the power and spectrum of the backward Yb-ASE. At the end of third stage, another WDM is used to monitor the power of the amplifier and forward Yb-ASE for comparison and then replaced by the AS-PBGF for Yb band parasitic lasing suppression. The backward Yb-ASE is also attenuated by splicing another piece of AS-PBGF ahead of the third stage. All of the output ports are angle cleaved to avoid the Fresnel reflection. The output spectrum is measured by an optical spectrum analyzer (OSA; Yokogawa AQ6370B). The AS-PBGF and the passive double-cladding fiber can be directly spliced by an arc fusion splicer (Fujikura FSM-60S) due to the all-solid structure. The forward and backward splicing losses between passive double-cladding fiber and the AS-PBGF were 0.487 and 3 dB, respectively. The high splicing loss was caused by the mismatch between mode field diameters and numerical apertures.

The AS-PBGF employed in our experiment has a bandgap at the region of 1,030–1,140 nm. The mode field diameter (MFD) of AS-PBGF is 10.9  $\mu\text{m}$  at the wavelength of 1,550 nm. The transmission spectrum is shown in Fig. 2.



**Fig. 1** Experimental setup



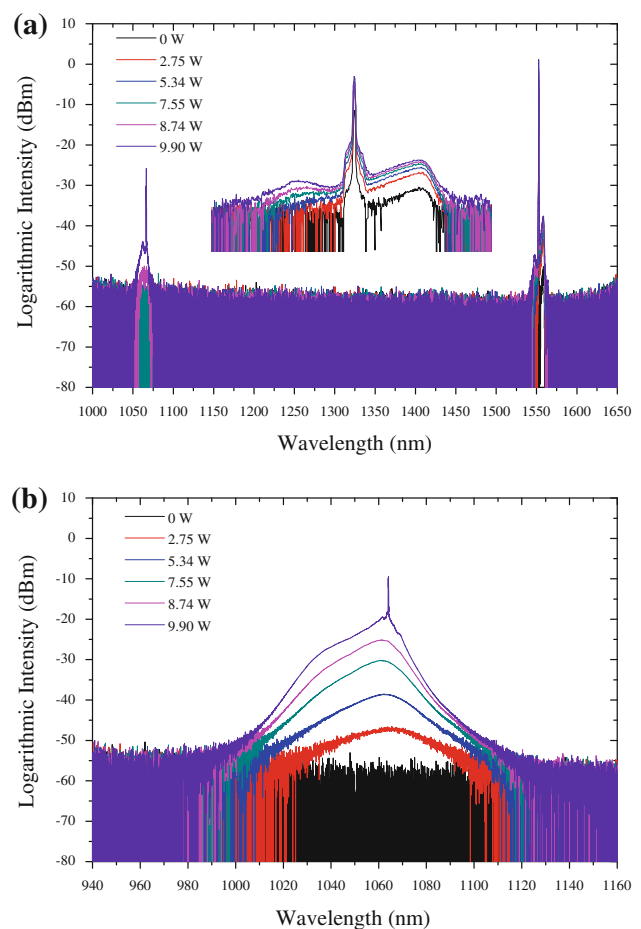
**Fig. 2** Transmission spectrum of the AS-PBGF

It can be seen that the loss is more than 20 dB with the length of 18 m in the Yb band, whereas it is very small in Er band. The utilized AS-PBGF has a measured transmission loss of 0.41 dB/km at 1,550 nm.

### 3 Experimental results and discussions

The spectra of the output laser without AS-PBGF were measured firstly by the OSA. The output and backward Yb-ASE spectrum evolutions with the increasing of pump power are illustrated in Fig. 3. The output spectra were straightforwardly measured without the utilization of WDM for the comparison of the signal and Yb-ASE. It can be seen that with the increasing of pump power, the Er band signal is amplified rapidly at first. When the pump power is more than 5 W, the Yb-ASE is growing obviously and the spectra of the seed do not show a significant change. Figure 3b also shows that the Yb-ASE appears even at the lower pump power, but increases rapidly with the increasing of pump power. When the pump power is around 10 W, the parasitic lasing appears both forward and backward. Under this pump power level, the output power of seed signal is limited to around 1.3 W without any parasitic lasing for stable amplifier operation. Compared with Fig. 3a, b, the parasitic lasing is not stable and the spectrum as well as the power of Yb-ASE is varying in time, which agrees with the experimental observation done by Grzegorz Sobon [11]. The amplifier system can be easily damaged under this circumstance. During our research, the active fiber was damaged more than five times by the parasitic lasing and self-pulsing effects in Yb band. All of these indicated the necessity of parasitic lasing suppression in the Er/Yb-co-doped fiber amplifiers, especially for high-power operation.

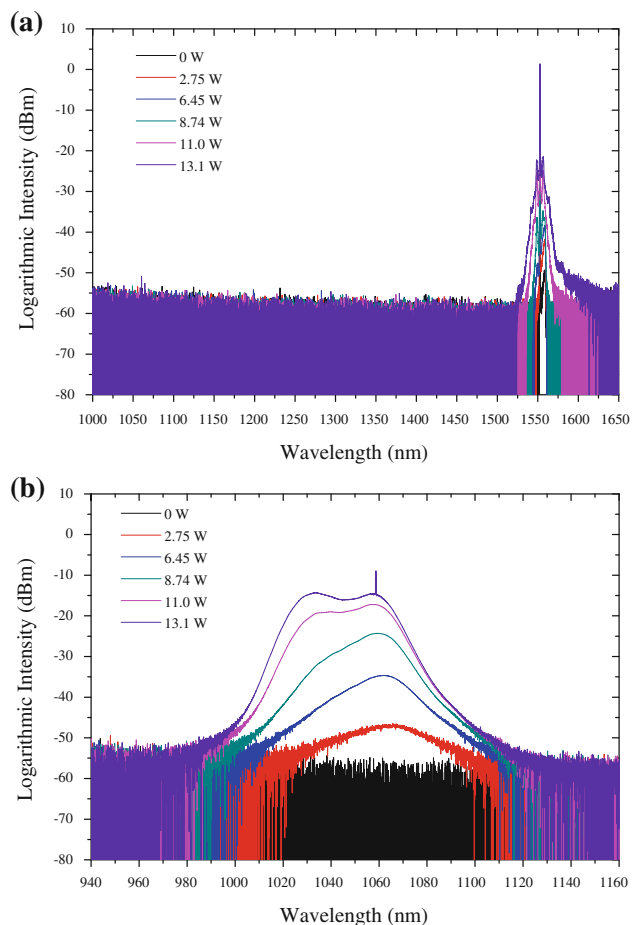
For the Yb band parasitic lasing suppression, 16-m-long AS-PBGF was spliced to the end of the power amplifier



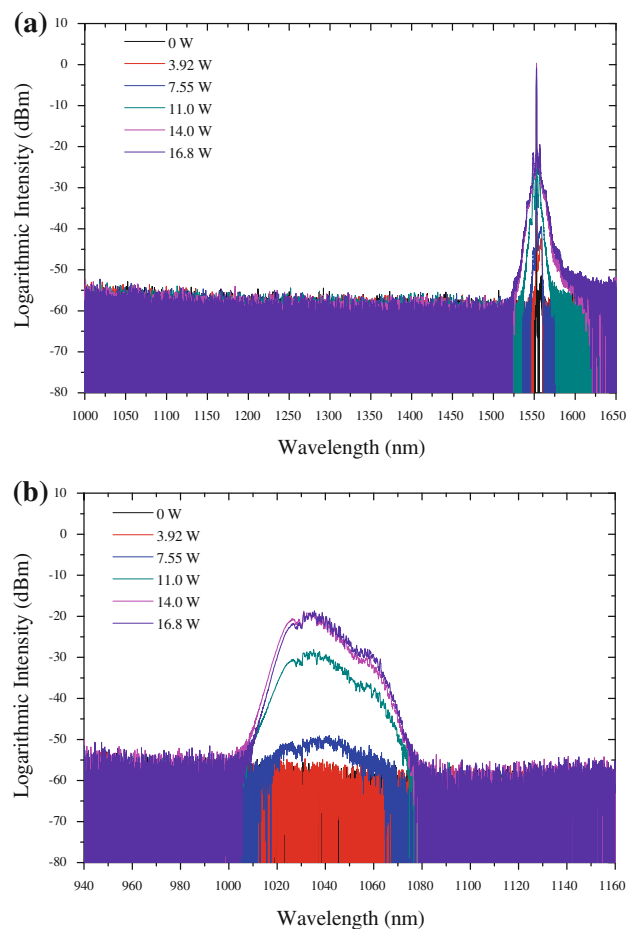
**Fig. 3** The measured output spectra, inset: enlarged view of the signal (a) and the backward Yb-ASE (b) without AS-PBGF

stage for forward Yb-ASE attenuation, as shown in Fig. 1. The output spectra were measured with the increasing of pump power and illustrated in Fig. 4a. It can be clearly seen that almost all the forward Yb-ASE is attenuated. But for the backward Yb-ASE, the parasitic lasing also emerged at the pump power of 13.1 W (see Fig. 4b), and the amplifier power is 1.8 W. And at the higher pump power, the modulation instability (MI) happens around the signal due to the high pulse energy and the small core active Er/Yb-co-doped fiber. The experiment of backward Yb-ASE attenuation was also done. Because of the lower power of forward Yb-ASE, the threshold of parasitic lasing is a bit lower than that of forward suppression. The output power of amplifier power is increased although the parasitic lasing still emerged at the higher pump power. This demonstrated that the control of forward and backward Yb-ASE is all necessary in order to build power-scalable and stable Er/Yb-co-doped fiber amplifier.

For this consideration, another segment of AS-PBGF (2 m) was spliced ahead of the third stage to attenuate the backward Yb-ASE, as shown in Fig. 1. Because of the



**Fig. 4** The evolution spectra of the signal (a) and backward Yb-ASE (b) versus the pump power with the forward utilization of AS-PBG



**Fig. 5** The evolution spectra of the signal (a) and backward Yb-ASE (b) versus the pump power with the utilization of AS-PBGF both forward and backward

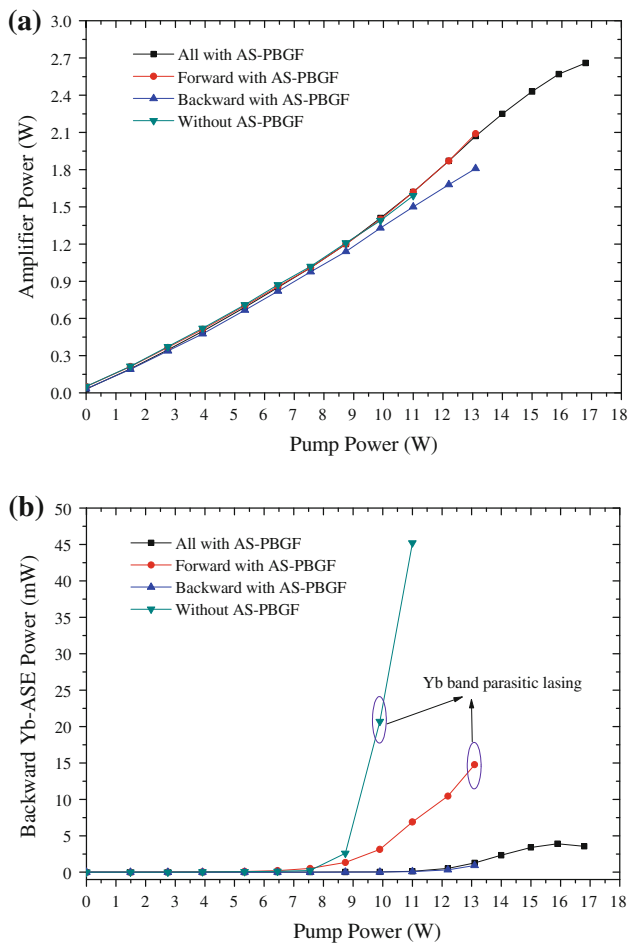
large core diameter of AS-PBGF and the small core of passive double-cladding fiber (6  $\mu\text{m}$ ), the splice loss between them is  $\sim 3$  dB. So, the seed power to feed the third stage is decreased to only 100 mW, but is also enough for the power amplifier stage. Also, the output power and the spectra of output and backward Yb-ASE were measured as shown in Fig. 5. It can be seen, with the backward utilization of AS-PBGF, that the threshold of parasitic lasing is improved dramatically, although the spectrum of the signal deteriorated by the MI. There is no parasitic lasing emerging both forward and backward even at the pump power of 16.8 W. The maximum amplifier power (2.66 W) is limited by the pump power of the LD as well as the dropping of the slope efficiency at higher pump powers.

The output power of amplifier was measured with and without AS-PBGF, as shown in Fig. 6a. It can be seen clearly that the maximum power for stable operation is raised dramatically without significant influence on the slope efficiency. The relative lower slope efficiency of the backward with AS-PBGF is caused by the high splice loss between the AS-PBGF and the passive DCF as well as the

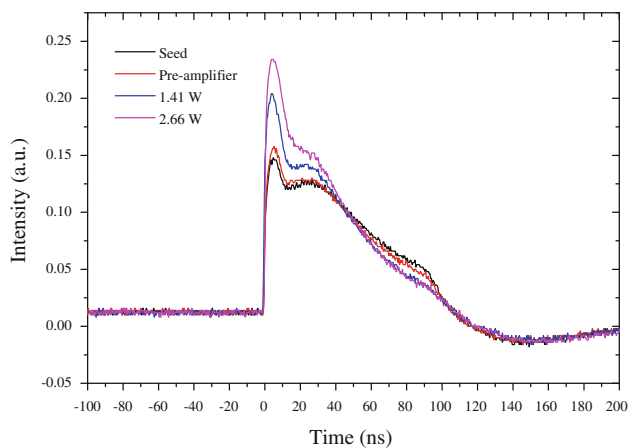
power of forward Yb-ASE. However, in other cases, the slope efficiency is not influenced by the utilization of AS-PBGF.

The power of backward Yb-ASE was also measured for comparison as shown in Fig. 6b. It increased rapidly without the utilization of AS-PBGF, and the Yb-ASE can be easily translated to parasitic lasing with higher pump powers. For the only forward utilization of AS-PBGF, the parasitic lasing can also appear although the Yb-ASE is decreased apparently. With the only backward utilization of AS-PBGF, the backward Yb-ASE power is reduced to a very low level. As to the utilization of AS-PBGF both forward and backward, the backward Yb-ASE power is limited to  $\sim 4$  mW even at the maximum pump power. The forward Yb-ASE powers are almost filtered due to the long length of AS-PBGF for forward Yb-ASE attenuation. This makes the threshold of parasitic lasing to a significant level and scales the maximum amplifier power for safe operation.

For the long pulse operating at KHz level, the gain saturation can occur at higher powers [14]. The pulse



**Fig. 6** The amplifier powers (a) and the Yb-ASE powers (b) with and without the utilization of AS-PBGF



**Fig. 7** Input and output pulse profiles

profile was measured for the confirmation of gain saturation effect, illustrated in Fig. 7. It can be seen that the leading edge of the pulse got a higher gain than the rest. This is due to the depletion of population inversion by the leading edge [15]. For the high-power saturated laser

amplifiers, this pulse distortion can be compensated by a proper shaping of the input pulse [14–16].

## 4 Conclusions

The AS-PBGF with a bandgap between 1,030 and 1,140 nm has been used to suppress the Yb band parasitic lasing for the pulsed Er/Yb-co-doped fiber amplifier. A maximum average output power of 2.66 W was achieved. The Yb band parasitic lasing has been well suppressed, and the maximum amplifier power for stable operation has been increased dramatically with the utilization of AS-PBGF. The results have demonstrated that this method is effective for the power-scalable Er/Yb-co-doped pulsed fiber amplifiers.

The seed laser used in our experiment is a modulated fiber laser; because of its low repetition frequency and the small core of the active DCF, the MI can be easily excited to broaden the spectrum width. The amplifier power has been limited to a certain degree. A proper seed laser as well as the rare earth-doped fibers is significant for the high-power fiber amplifiers. Besides, the AS-PBGF is not specially designed for our Er/Yb-co-doped fiber amplifiers; the core diameter and numerical aperture are not matched with the DCF utilized in our experiment. The total loss has increased in the system. Furthermore, the bandgap of short-wavelength Yb-ASE in 1,000–1,030 nm is not included in the bandgap region of AS-PBGF (1,030–1,140 nm). These two aspects will be improved for the high-power operations. However, the efficiency and simple configuration can also be seen in the experiment. We believe that this method is efficient for the power scaling of Er/Yb-co-doped pulsed fiber amplifiers as well as continuous wave amplifiers.

**Acknowledgments** This work was supported by National Natural Science Foundation of China (NSFC 61007054), Doctoral Program of High School Research Fund (20104408110002), Key Program of Basic Research Project of Shenzhen (JC201005250048A), Improvement and Development Project of Shenzhen Key Lab (CXB201005240014A), National Key Basic Research and Development Program of China (2010CB735904), the Science and Technology Project of Shenzhen City (JC201105170693A) and Natural Science Foundation of SZU (201203).

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