Optical properties of ytterbium-doped tandem-pumped fiber oscillator

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With the rapid development of ytterbium-doped fiber lasers, some obtrusive limitations on power scaling appeared. In order to avoid these problems, a scheme called tandem pumping is introduced into the fiber laser field. In this paper, the optical properties of an ytterbium-doped tandem-pumped fiber oscillator are presented. According to the oscillator profile, the proper gain fiber type and pump wavelength range are picked out, under the comprehensive consideration of laser conversion efficiency and beam quality. In addition, the photodarkening performances of tandem pumping lasers and conventional ones are compared based on practical application, with all possible impact parameters taken into account. Moreover, an all-fibered tandem-pumped oscillator centered at 1079.5 nm is built, in the way of clad pumping by a 1030-nm fiber laser. The laser power of the oscillator reaches 7 W, with an opto-optic efficiency of 82.4%.

Keywords: ytterbium-doped fiber laser, tandem-pumped fiber oscillator, premium pump wavelength, photodarkening performances

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1. Introduction

Ytterbium-doped fiber lasers (YDFLs) are well known for their excellent beam quality, high efficiency, reliability, and compactness. There has been astonishingly rapid progress for YDFLs over the last decades, with the powers of which increasing from a few watts to several kilowatts.[1–6] However, the power scaling of YDFLs is not straightforward and some obtrusive limits have arisen. These limitations include thermal self-focusing, onset of nonlinear effects, facet damage, and the availability of high brightness pump diodes.[7–10]

To alleviate these critical problems at the same time, or some of them without compromising the others, a method called tandem pumping is proposed.[3,11] Fiber lasers with wavelength between 1010 nm and 1030 nm are adopted as pump sources in the scheme, instead of laser diodes at 9xx nm. Because of the smaller difference between the pump and laser wavelengths, this approach leads to a lower quantum defect and then a reduced thermal load, which results in easier thermal management and less thermal beam distortions. Because of the higher brightness of pump sources, the available pump power for a given fiber geometry is scaled in the scheme. Furthermore, tandem-pumped fiber lasers have a lower photodarkening (PD) rate, and better beam quality as a result of less gain for unwanted modes.[12] In addition, there is no need for additional wavelength stabilization of pump sources in a tandem pumping scheme, as in the case of diode pumping.

Due to these advantages, studies on tandem pumping have drawn much attention and there are many reports on it. Some showed an extremely high output power from a tandem-pumped amplifier, with a thin-disk laser as the pump source.[13–16] Other fiber laser-pumped ones involved core pumping to solve the low-absorption problems of ytterbium (Yb) ions around 1 μm.[17–19] Besides, all of them focused on the experiments of tandem pumping lasers, while the optical properties and mechanism of this kind of laser were seldom discussed.

In this paper, optical properties of the tandem-pumped fiber oscillator are studied and discussed. The criteria for pump wavelength selection are presented with laser conversion efficiency and beam quality as the optimization parameters. Compared with conventional fiber lasers, the photodarkening properties of tandem pumping lasers are studied, with all practical impact parameters taken into account. Besides, a 1080-nm all-fibered tandem-pumped fiber oscillator is built in experiment, pumped by a 1030-nm fiber laser. The oscillator adopts the way of clad pumping, and has an opto-optic efficiency of 82.4% with only the absorbed pump considered.

2. Analysis of optical properties of tandem-pumped fiber oscillator

2.1. Appropriate gain fiber type and pump wavelengths for tandem-pumped oscillators

As for gain fiber in a tandem-pumped fiber laser, because of the smaller absorption cross-sections of tandem pumping wavelengths between 1010 nm and 1030 nm than that of 975 nm, the cladding absorption of the pump should be high enough in order to achieve sufficient absorption of pump light.

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This requires the gain fiber to have a high doping level and/or a large core to clad ratio. Both of them help the gain fiber to absorb more pump light in a relatively small length, which reduces the risk of nonlinearity effects as well.

Other than the gain fiber type, the pump wavelength also has a great impact on the operation of a tandem-pumped laser. Although the appropriate pump wavelength for a tandem-pumped laser covers a wide range, a premium pump wavelength does exist, which is mainly weighed by laser conversion efficiency and laser beam quality here. The calculations are based on steady-state rate equations[20] and beam quality factors equations.[21] From the aspect of laser conversion efficiency, the premium pump wavelength could be determined, as shown in Fig. 1. The gain fibers used in the simulation have the same size parameters with the one adopted in the experiment, but with a different Yb doping level as 12000 ppm (wt.) (parts per million by weight) in Fig. 1(a) and 15000 ppm (wt.) in Fig. 1(b). In this paper, ppm means parts per million. From the figure, the opto-optic efficiency reaches the peak under the pump wavelength of 1024 nm in Fig. 1(a) and 1025 nm in Fig. 1(b), which is called premium pump wavelength in laser efficiency here. In addition, laser efficiencies at some of the simulated pump wavelengths differ slightly, which defines a premium pump range. In Fig. 1, the premium pump range is 1019 nm–1028 nm and 1020 nm–1030 nm, respectively.

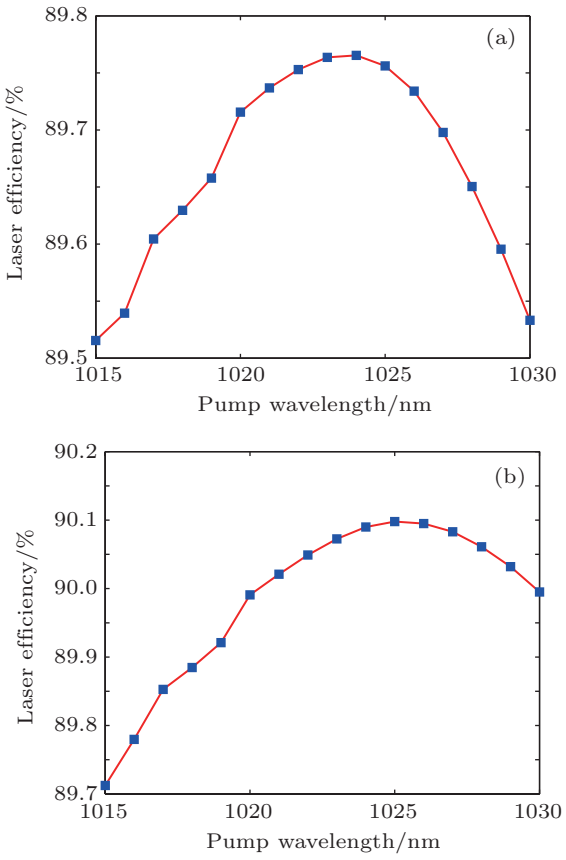


Fig. 1. (color online) Simulated laser efficiency as a function of pump wavelength with Yb doping level of the gain fiber as (a) 12000 ppm (wt.) and (b) 15000 ppm (wt.).

The premium pump wavelength in laser efficiency differs among various gain fibers. It depends on Yb doping levels and core diameters, as shown in Fig. 2. From the figure, it is seen that the premium pump wavelength moves towards longer wavelength as the Yb concentration grows higher or the core size grows larger. According to what is discussed above, a high doping level (usually more than 10000 ppm (wt.)) and a large core (usually larger than 20 μm) is demanded for the gain fiber in a tandem-pumped laser, so the pump wavelength adopted in this kind of laser is better to be longer than 1023 nm.

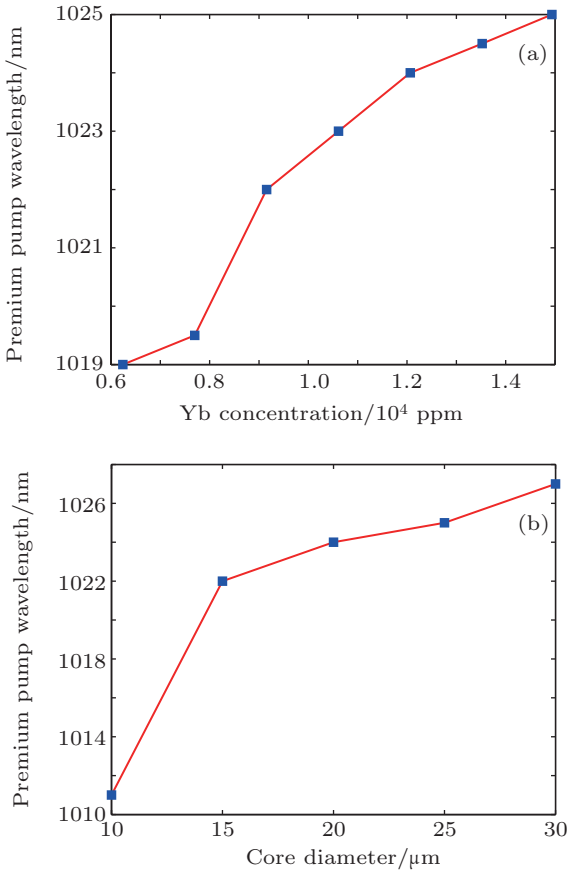


Fig. 2. (color online) Simulated variation of premium pump wavelength in efficiency with (a) Yb concentration and (b) core diameter of the gain fiber.

From the aspect of beam quality, pump wavelength has an impact on the output laser, which is the result of various gain ratios for each mode under different pump wavelengths. Figure 3(a) presents the transversal distribution of normalized gain under distinct pump wavelengths, and figure 3(b) displays the variation of normalized gain for each mode with pump wavelength. In order to analyze the interaction among more modes, a fiber with larger core is adopted in the simulation. The gain fiber used is a 30/130 μm one, with a doping level of 7000 ppm (wt.). As the high-order modes are mainly located in the core edge while the low-order ones are located in the center, it is easily seen from the figure that the gains for high-order modes decrease faster than those for low-order ones,

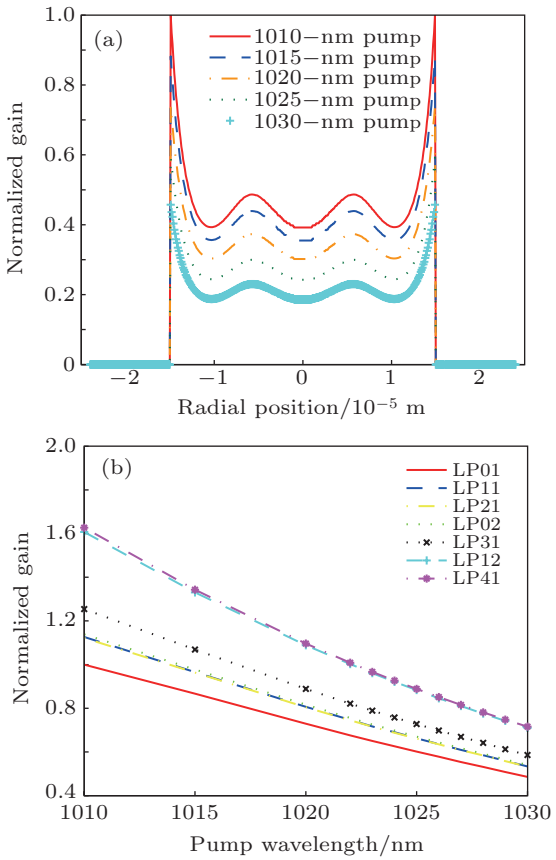


Fig. 3. (color online) Simulated (a) transversal distribution of normalized gain in fiber core under distinct pump wavelengths and (b) normalized gain variation of each mode with pump wavelength.

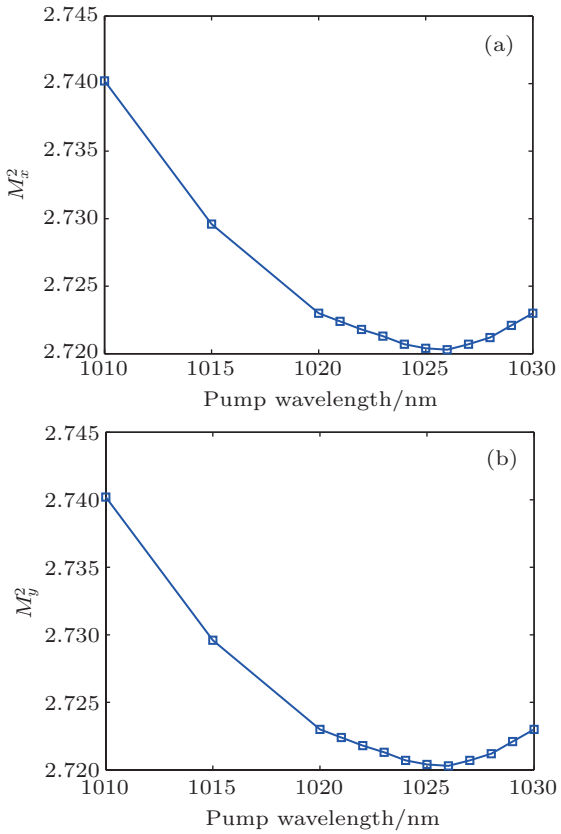


Fig. 4. (color online) Simulated beam quality factors as a function of pump wavelength: (a) M_x^2, (b) M_y^2.

with the growth of pump wavelength. Smaller power proportions for high-order modes means a better beam quality. As the variation rates of gains are different among all the modes, the smallest M^2 factors exist when high-order modes take the smallest ratio, as shown in Fig. 4 where the premium pump wavelength in beam quality is 1026 nm. Similar to Fig. 1, there is a premium pump wavelength range in Fig. 4 of 1020 nm–1030 nm.

The premium pump wavelength in laser beam quality is influenced by the fiber clad diameter, but has nothing to do with the Yb doping level and the core diameter. As shown in Fig. 5, with the increase of the clad diameter, the premium pump wavelength moves towards longer wavelength, but the change is little. Based on the ordinary fiber clad size, the premium pump wavelength in laser beam quality is usually longer than 1026 nm.

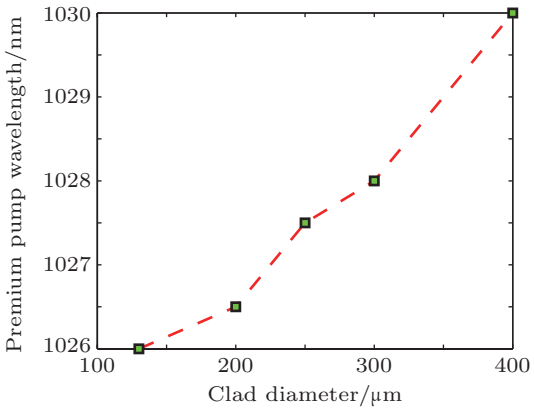


Fig. 5. (color online) Simulated variation of premium pump wavelength in beam quality with fiber clad diameter.

Taking pump wavelength selection criteria based on laser efficiency and beam quality as a whole, as for gain fibers used in tandem-pumped lasers, the premium pump wavelength range is 1020 nm–1030 nm. Therefore, in the experiment of the tandem-pumped oscillator illustrated in Section 3, 1030 nm is chosen as the pump wavelength from the premium pump wavelength range.

2.2. Comparison of PD rates between tandem-pumped lasers and conventional ones

As for Yb-doped fiber lasers, the photodarkening effect is a serious problem, which could affect the output power and the stability of fiber lasers.[22,23] Studies found that the number density of excited Yb ions is closely correlated to photodarkening, and an exponent of 7[24] or 4.3[25] is testified in the power-law dependence of photodarkening rate constant on the excited Yb ions concentration. In the same fiber, the excited Yb ions concentration could be replaced by Yb inversion in the power-law relationship. As we know, with the identical gain fiber, the Yb inversion in a tandem-pumped laser is much smaller than that in a conventional one. However, it cannot

be simply concluded that the possibility of PD in a tandem-pumped laser is so small as well. Due to the different criterion for gain fiber selection between the tandem-pumped laser and the conventional one, the PD rates of the two kinds of lasers should be compared according to the excited Yb concentration, with the doping level and the inversion rate considered as a whole.

Based on the criteria for gain fiber selection illustrated above, the gain fiber adopted in a tandem-pumped laser is usually doped higher than that in a traditional one. This results in a larger PD rate with the same inversion level. However, the inversion rates in the two lasers are influenced by quite a few parameters. Figure 6 describes the relationship between the maximum inversion rate and Yb concentration, with 1030 nm and 975 nm as the pump wavelengths respectively and 1080 nm as the laser wavelength. The fibers employed have the same size and the pump is absorbed to the same extent in the simulation. The figure shows that the inversion rate has nothing to do with the doping level, and it only depends on pump wavelength in this situation.

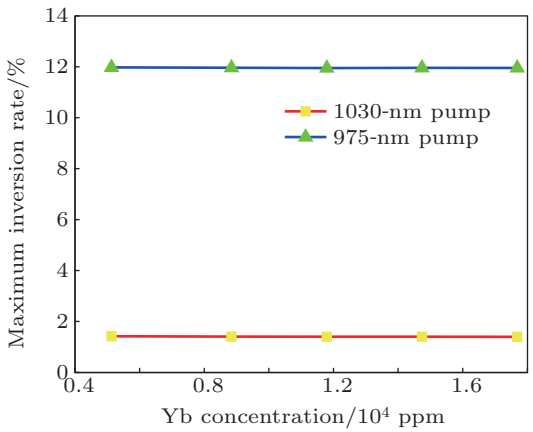


Fig. 6. (color online) Simulated variation of maximum inversion rate with Yb concentration.

Figure 7 displays the impact of fiber size on the maximum inversion rate, in a highly doped fiber and a relatively low doped one. The pump and laser wavelengths are the same for two fibers in the calculation, and the pump absorption ratios are set identical. In the figure, the maximum inversion rate is linearly proportional to the fiber's core to clad ratio; fiber with a larger core and a smaller clad has a larger inversion when laser is generated. The inversion rate is not influenced by the doping level as well. Besides, based on the calculation, the inversion rate in a laser has nothing to do with the pump power.

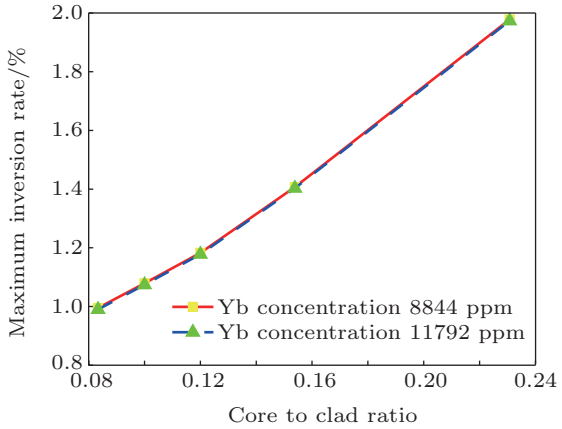


Fig. 7. (color online) Simulated variation of maximum inversion with fiber core to clad ratio.

From what is simulated and discussed above, the number density of excited Yb ions in a laser depends on several parameters. With all the influences taken into account, the PD rate in a tandem-pumped fiber laser and a traditional one could be quantitatively compared. Here, a 20/130-μm fiber (Fiber 1#) with a concentration of 10000 ppm (wt.) is chosen as the gain fiber for the tandem-pumped laser (which is the same as the one used in the experiment presented below), and a 20/400-μm fiber (Fiber 2#) with a concentration of 7500 ppm (wt.) is selected for the conventional one as is usually done. The lengths of both the gain fibers are set to absorb the pump light by 13 dB. The comparison between the two lasers is shown in Table 1.

Table 1. Comparison of characteristic parameters between tandem-pumped and conventional lasers.

Laser type	Gain fiber	Pump wavelength/nm	Fiber doping level/ppm	Maximum inversion rate/%	Maximum excited Yb concentration/ppm
Tandem pumped	Fiber 1#	1030	10000	1.4	140
Conventional	Fiber 2#	975	7500	2.4	180

From the data listed in Table 1, it is obvious that the concentration of excited Yb ions is smaller in the tandem-pumped laser than in the conventional one, but the difference is not that much. The maximum excited Yb concentration in Fiber 2# is 1.3 times as much as that in Fiber 1#, which is much smaller than the inversion difference shown in Fig. 6. However, as the PD rate is power-law related to the excited Yb density, taking the exponent of 7 as an example, such difference in excited Yb concentration could result in six times variance in PD performances between two lasers. Therefore, tandem-pumped lasers do have an advantage in preventing PD effect over conventional ones, but the advantage is not as much as the variance in inversion rate between the two types of lasers. The analyzing method supplied here presents a practical way to study the PD

effect in a tandem-pumped fiber laser, with all the possible impact factors involved. According to the analysis, if the doping level of the gain fiber in a tandem-pumped laser becomes too high, the PD phenomenon may appear earlier in the laser than in a traditional one.

3. Experiment and results

Based on the pump wavelength selection criteria, a 1030-nm fiber laser is chosen as the pump source for the tandem-pumped fiber laser. The experimental setup of the proposed 1080-nm fiber oscillator is displayed in Fig. 8. A fiber oscillator operating at 1030 nm is adopted as the pump, with laser emitting from a 11-μm core. A (1+1)×1 combiner couples the pump into the gain fiber, in the way of side pumping. The pump fiber of the combiner has a size of 105/125 μm, and the signal one has a size of 20/125 μm. A pair of fiber Bragg gratings (FBGs) centered at 1080 nm are connected to both ends of the gain fiber, with reflectivity of 98% (HR FBG) and 10% (OC FBG) respectively. The gain fiber is a commercial double-clad ytterbium-doped one, with a core diameter of 20 μm and a clad diameter of 130 μm. The numerical apertures (NAs) of the core and the cladding are 0.075 and 0.46, respectively. The pump leakage after the OC FBG is used to leak out the unabsorbed pump light. As the pump is side-coupled into the gain fiber, the scheme of the oscillator could also be applied to a tandem-pumped fiber amplifier, just with FBGs excluded.

Limited by the experiment condition, the two FBGs in hand are etched on passive fibers with core diameters of 20 μm and clad diameters of 400 μm. Because of the mismatch on clad diameters between the tailed fibers of FBGs and the gain fiber, two cladding tapers are introduced in the laser configuration, shown in Fig. 8 as taper 2 and taper 3. The two tapers are manufactured by HF tapering method, which only tapers fiber cladding without affecting the core size. Another taper marked as taper 1 connecting the (1+1)×1 combiner and the HR FBG is brought in for pump transmission. The cladding of FBG fiber is drawn to 125 μm by fiber fusion equipment to match the combiner output fiber with the size of 20/125 μm. As clad NAs of the combiner output fiber and the gain fiber is both 0.46, taper 1 and taper 2 ensure the Lagrange invariant of the input fiber is equal to that of the output one. Therefore, these two tapers would not affect the efficiency of pump injection into the gain fiber. This taper-included configuration could be used in many fiber lasers with fiber size mismatch problems.

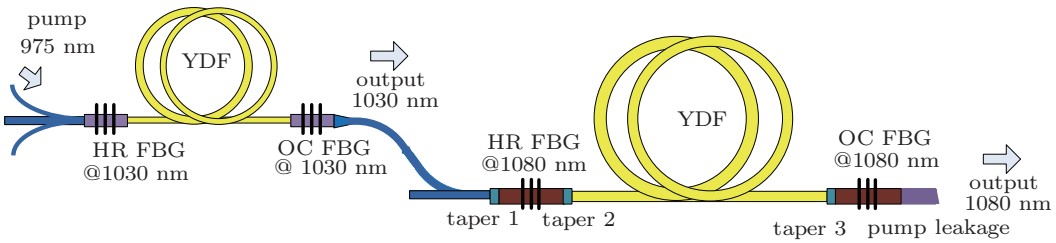


Fig. 8. (color online) Experimental setup of the tandem-pumped fiber oscillator.

The output spectrum of the fiber oscillator is shown in Fig. 9. The output laser is centered at 1079.5 nm, with a width of 1.08 nm. Due to experimental limitation, the gain fiber adopted is only 9 m, which is much shorter than the length needed for sufficient pump absorption (which is 50 m here). The gain fiber used in this experiment has a relatively large core to clad ratio, but the core doping level is not high enough. Combined with a short fiber length, this results in plenty of pump unabsorbed at the end of the gain fiber. Based on the criteria for gain fiber selection, fiber with higher doping concentration and maybe a larger core to clad ratio than the one adopted here would be a better choice in a tandem-pumping fiber laser. The maximum laser power of the oscillator reaches 7 W under the 22-W pump, with 8.5 W of the pump unabsorbed. The experimented and simulated output powers are displayed in Fig. 10, showing simulated results a little higher than experimented ones. Taking only the absorbed pump power into account, the opto-optic efficiency of the oscillator reaches 82.4%.

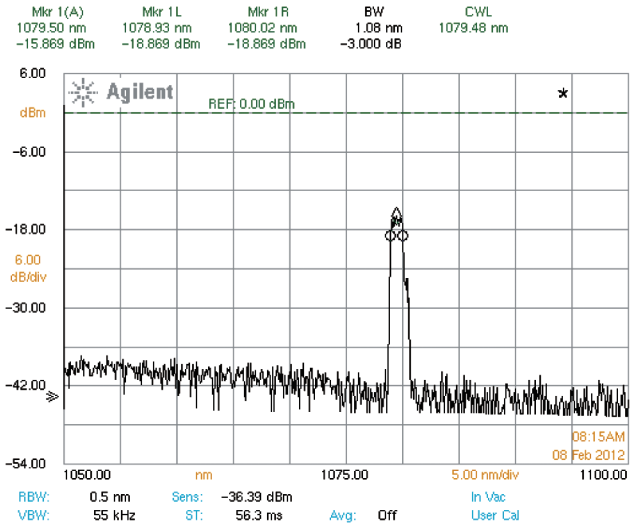


Fig. 9. (color online) Output spectrum of the 1080-nm fiber oscillator.

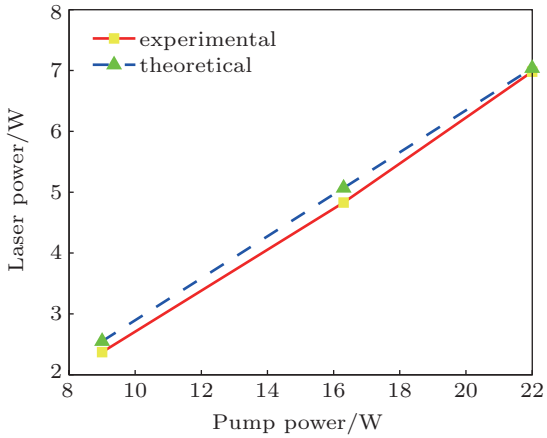


Fig. 10. (color online) Experimented and simulated output laser power as a function of the incident pump.

In the laser configuration, as the pump source involved is of very high brightness, there is a large potential for pump power scaling in the tandem-pumped laser. Based on combining technology, beams of up to 37 such pump sources could be combined into one pump fiber. Together with the adoption of $(N+1)\times 1$ combiner, the pump injection power is expanded much more. Moreover, as the pump is injected into the gain fiber sideways, the oscillator profile could be applied to the amplifier as well, just with the fiber gratings excluded.

4. Conclusion

The optical properties of the tandem-pumped fiber oscillator are illustrated in this paper. Based on the oscillator profile, the gain fiber with high doping level and/or large core to clad ratio is thought to be appropriate for a tandem-pumped laser. With the aim of high laser efficiency and good beam quality, a premium pump wavelength range is determined. The premium pump wavelength is influenced by doping level, core diameter, and clad diameter of the gain fiber. In addition, the PD performances of a tandem pumped laser and a conventional one are compared, with all possible influence factors considered as a whole. It is found that tandem pumped fiber laser is less easily photodarkened than the conventional one, but the advantage is not as much as that in the inversion rate. Moreover, an all-fibered tandem pumped fiber oscillator is built in experiment, in the way of clad pumping with a 1030-nm oscillator as the pump source. The oscillator has an output laser power of 7 W at 1079.5 nm. Taking only the absorbed pump into account, the opto-optic efficiency of the laser reaches 82.4%.

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