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Distributed and Side-Pumped Fiber Laser Using a Laser Diode Bar Stack

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ABSTRACT A distributed, side-pumped Yb^{3+}-doped fiber laser is demonstrated using a laser diode stack as a pump source. Four subwavelength gratings fabricated on the same fused-silica substrate were aligned with four laser diode bars of the laser diode stack package for coupling pump light into double-clad fibers. Under the 975-nm pump power of 124.6 W, a 58 W Yb^{3+}-doped fiber laser has been demonstrated. Due to the distributed pumping scheme, the nonuniformity of fiber heating from quantum defect is reduced as seen from the narrow linewidth of the fiber laser output across the entire pump power range. As a further step, the genetic algorithm method was used to design an aperiodic grating with a 40-nm fine structure. The adoption of the aperiodic grating, fabricated by using the E-beam lithography process, reduced the edge coupling loss effect, which allowed to reach 70% coupling efficiency. The side pumping scheme is compact and efficient, and power scaling is possible with more laser diode bars in the laser diode bar stacks. To the best of our knowledge, this is the first demonstration of a distributed pumped fiber laser using a laser diode bar stack as the pump source.

INDEX TERMS Optical pumping, gratings, fiber lasers, semiconductor laser arrays.

I. INTRODUCTION

Pump sources and pumping configurations play essential roles in advancing high power fiber laser systems in terms of system efficiency, power scalability, and compactness [1], [2]. Laser diode bars (LDBs) and laser diode bar stacks (LDBSs) are reliable, high-power pump sources, which have been widely used in various applications [3]–[8]. In traditional pumping configurations, multi-mode fused fiber bundle combiners have been successfully adopted to lower the coupling loss compared with bulk optical components. To further scale up the total pump power, distributed pumping techniques using a series of fibers have been proposed [9], [10]. Recently, the distributed pumping scheme is achieved by cascading stages of bi-directionally-pumped and fiber-fused-bundle couplers [11], [12]. When the pump source is scaled to higher power LDBS with much higher count of bars and emitters, the pump power is limited by the complexity of the pump source itself. Active alignments between each single emitter and the delivery fiber of the LDB are needed. So far, the LDBS has mainly been used in spatially combined multiplexing schemes due to its high slow-axis divergence angle [13]. This shows that advanced pump sources and techniques are still needed to power scale and improve fiber laser performance. A compact, highly efficient grating side-pumped configuration is implemented. Using a specially designed grating coupler, the emission from LDB/LDBS is directly side-launched into the cladding of a double-clad Yb^{3+} doped fiber through a set

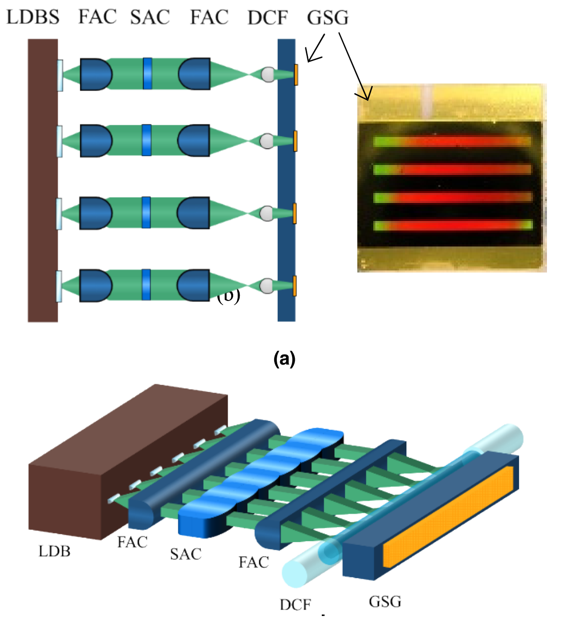

FIGURE 1. **(a) Schematic diagram of the whole LDBS side-pumping coupler. The inset photo shows the 4 subwavelength gratings with gold coating. LDBS: Laser diode bar stack, FAC: Fast axis collimator lens, SAC: Slow axis collimator lens, DCF: Double clad fiber, GSG: Gold-embedded silica grating. (b) Schematic diagram of the GSG side-coupling system for each LDB.**

of brightness-preserving focusing/collimating optics. With the proposed technique, fiber laser system power scaling can be pursued with substantially more LDBs in the LDBS package.

II. LDBS SIDE-PUMPED CONFIGURATION

A four-bar 975 nm LDBS was used as the pump source in the following laser experiment. A schematic diagram of the grating-based fiber coupler is shown in Fig. 1. The commercial 1-cm-long 975 nm LDBs in LDBS were separated by a vertical pitch of 1.8 mm. Each LDB consisted of 19 emitters with a 500 μm pitch. The outputs of the emitters were passed through a series collimation lens to collectively form four 1-cm-wide and 1-mm-thick parallel beams, one per each LDB. As shown in Fig. 1.a, each LDB had a corresponding 1-cm-long sub-wavelength grating on the opposite side of the double clad fiber (DCF). The four gratings were integrated onto one silica substrate with a dimension of 12×12 mm with the vertical pitch of 1.8 mm to match the pitch between the LDBs in a LDBS. Four passive DCFs (LIEKKI 20/400 DC) with the inner-cladding diameter of 400 μm, cladding numerical aperture (NA) of 0.46, core diameter of 20 μm, and core NA of 0.08 were attached to the other side of the substrate. The gap between the fiber cladding and silica substrate was filled with index-matching gel to minimize scattering loss. The normally incident beams were diffracted into $\pm$1st orders and propagated inside the outer cladding of the DCFs based on total internal reflection.

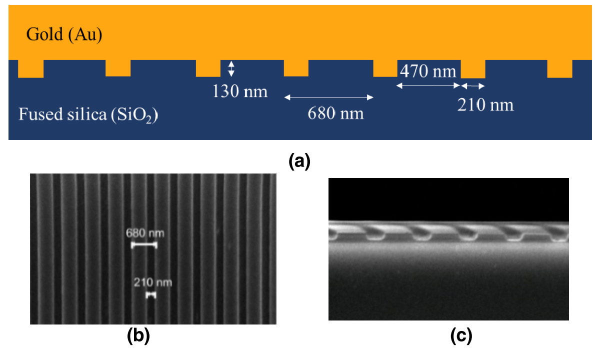

FIGURE 2. **(a) Schematic design of the 1 cm gold-embedded periotic grating, (b) top-view SEM image, and (c) side-view SEM image.**

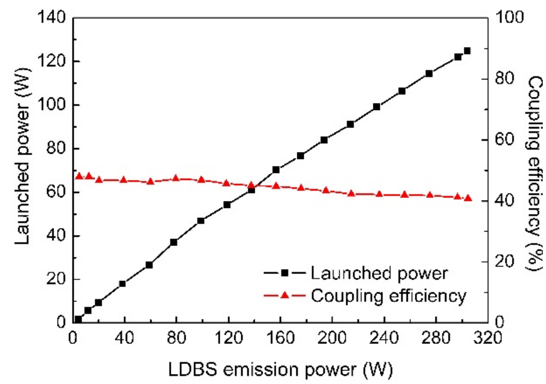

FIGURE 3. **The dependences of the launched pump power and coupling efficiency on the LDBS emission power.**

Figure 2 represents the structure and SEM photos of each gold-embedded silica grating. The grating pitch was chosen based on the LDB wavelength and the required diffraction angle. The diffraction angle must be larger than the critical angle of the fiber inner cladding. In general, there is no simple or straightforward design rule for the groove depth and width to date. The optimal design for the highest grating diffraction efficiency is obtained with the RSoft DiffractMod commercial software using rigorous coupled-wave analysis. The utilized refractive index n and extinction coefficient k were 0.13 and 6, respectively. Based on our fabrication technology, a trapezoid shaped groove wall with an angle of approximately 70Âř was routinely obtained [14] and thus adopted in the numerical simulations. The simulation results indicated the optimal grating pitch, groove width, and groove depth of 680 nm, 210 nm, and 130 nm, respectively. To achieve precise grating groove dimension control, E-beam lithography was used to define the grating pattern. The gold-embedded silica binary grating structure was utilized to ensure stable operation under high power [15]. In addition, the gold surfaces were contacted with a water-cooling mount for heat dissipation.

The coupling efficiency from LDBS to these four passive 400 μm fibers as a function of the launched laser power was measured. As shown in Fig. 3, the maximum coupled

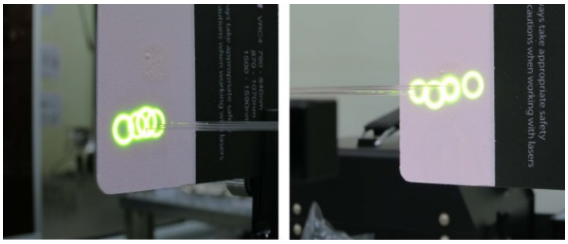

FIGURE 4. The transverse far-field mode patterns of the four coupled beams from the two end faces of the double-clad fibers.

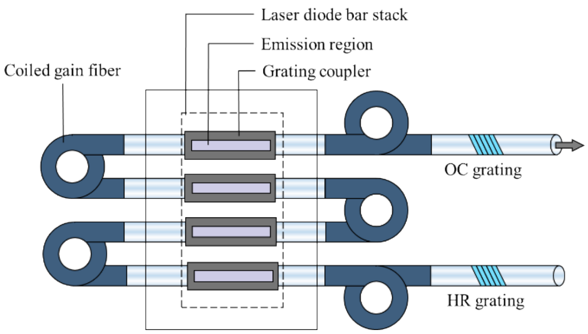

FIGURE 5. Schematic diagram of the distributed side-pumped Yb^{3+}-doped fiber laser.

pump power was 124.6 W under the LDBS power of 304.4 W with the efficiency of 40.9%. We observed that water-cooled grating couplers had a slight decay in coupling efficiency under high LDBS power operation. The coupling efficiency was near 50% at low pump power. The efficiency decay could be caused by the zero-order grating diffraction, which was back-coupled into the LDBS, degrading the LDBS optical performance.

The transverse far-field mode patterns from the four DCFs, into which LDBS power was coupled, were visualized using an IR sensor card, as shown in Fig. 4. The observed donut shapes were formed because of the relatively large inner clad numerical aperture.

III. LDBS SIDE-PUMPED HIGH-POWER FIBER LASERS

In order to form a distributed pumped fiber laser module, each passive double-clad fiber was spliced with an Yb^{3+}-doped DCF section, as shown in Fig. 5. The laser cavity was formed by a high-reflectivity fiber Bragg grating (FBG) as the cavity end mirror and a low reflectivity FBG that acted as an output coupler. Since the pump propagated in both directions in the fiber, both the gain and thermal distribution in the fiber cavity were much more symmetric and uniform than those in the conventional end-pumping schemes.

In order to optimize the LDBS-side-pumped fiber laser slope efficiency, LIEKKI™Application Designer was utilized to determine the proper gain fiber length and FBG reflectance in such a bi-directional pumped laser system [16]. Based on the simulation results, the optimal fiber length for each gain section was 10 m, and the reflectivity of the output coupler was 6%. Figure 6 shows the comparison between the experiment and LIEKKI simulation results based on the same operating parameters as the experimental case. An excellent agreement was achieved. The fiber laser slope efficiency was nearly 50% with a threshold of 9.25 W. To the best of our knowledge, this is the first demonstration of a distributed pumped fiber laser using LDBS as the pump source.

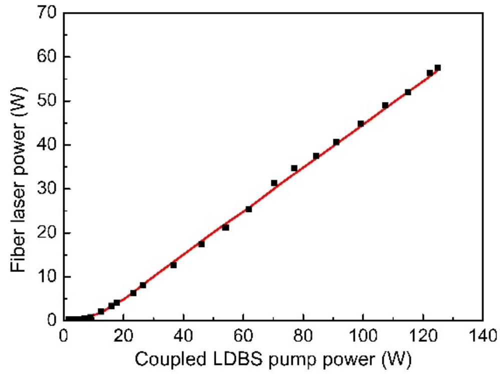

FIGURE 6. The experiment (black markers) and simulation (red line) results of the Yb^{3+}-doped fiber laser power.

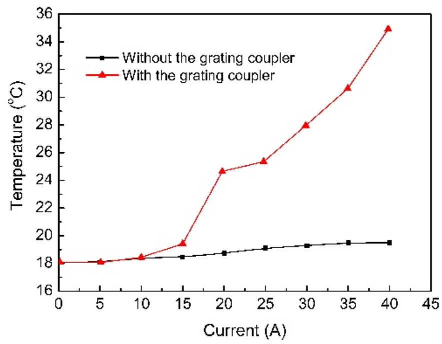

FIGURE 7. The impact of the zero-order diffraction from the grating coupler on the LDBS substrate temperature.

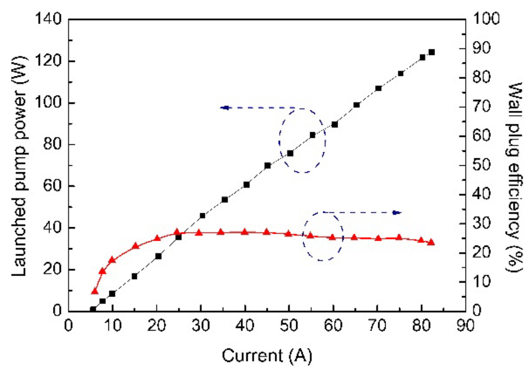

FIGURE 8. The dependences of the launched pump power and wall plug efficiency on the LDBS driving current.

IV. DISCUSSION

A. WALL PLUG EFFICIENCY

The LDBS temperature increased rapidly from room temperature when attached to the grating coupler, as shown by the

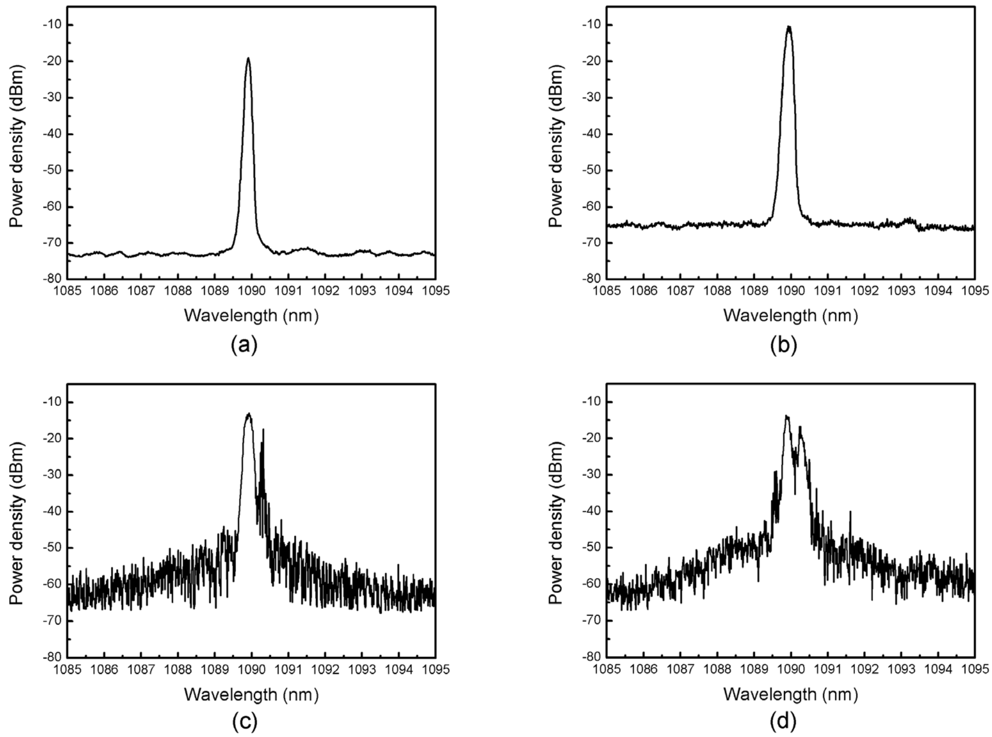

FIGURE 9. The fiber laser spectra at different output powers. (a) 1 W, (b) 8 W, (c) 25 W, and (d) 50 W.

red triangular markers in Fig. 7. In order to operate the LDBS safely, the injection current was limited to 40 A. Since the LDBS temperature remained near room temperature when the grating coupler was removed, this indicated that the LDBS emission light was back-coupled into the LDBS itself by the zero-order diffraction of the grating. Note that decreasing the zero-order diffraction may reduce the 1st-order diffraction angle, which will reduce the coupling efficiency. Furthermore, because the back-coupled light was converted into heat, this influenced the laser temperature stability. The back-coupled light also affected the LDBS output power. Indeed, the 975 nm LDBS output powers measured before and after attaching the grating couplers were substantially different. This was found to be the reason for the lower coupling efficiency at high pump powers, as shown in Fig. 3. The LDBS power decreases even further with increasing injection current. The measured coupling efficiency drops by almost 10% with the LDBS power raising from 0 to 304.4 W. Therefore, the results in Fig. 3 are better represented by Fig. 8 where the wall plug efficiency is indicated. The figure shows that the efficiency was maintained near 25% beyond the LDBS driving current of 20 A.

B. FIBER LASER LINEWIDTH

The fiber laser output spectrum was centered at 1090 nm as shown in Fig. 9. The linewidth was 0.11 nm, which was limited by the FBG. The side mode suppress ratio can reach 60 dB at low output power. Below the laser output power of 25 W, the laser emission spectrum was found to be narrow and clean. Above the 25 W laser output, the second spectrum maximum started to take off. In order to clarify the data shown in Fig. 9 on logarithmic scale, a linear scale data presentation is shown in Fig. 10 (a). The full width at half maximum laser linewidth was measured to be around 0.11 nm for all power levels without any broadening, which demonstrated the advantage of the distributed pumping scheme. We compared our laser linewidth results with those for a typical commercial high-power fiber laser module, LIEKKI OE-Yb-L-100, which exhibited the initial linewidth of 0.22 nm at the output power level of 0.8 W and broadened linewidth of $\sim$ 0.52 nm at 100 W, as shown in Fig. 10 (b). We believe that the spectrum broadening of the commercial module at high laser output powers is caused by thermal effects of the fiber cavity, since the LIEKKI module has a single-end pumping scheme. In our pumping scheme, the high-power pump was distributed between several Yb^{3+} fiber sections, whereby the thermal distribution in the fiber cavity was much more uniform, so that thermal effects were significantly alleviated. Therefore, the laser linewidth stayed the same regardless of the pump power. Furthermore, the narrow laser linewidth in this scheme is nearly as good as in the schemes using volume Bragg gratings as the end coupler [17], [18]. In Fig. 10 (a), the second peak around 1090.25 nm can also be seen at laser output powers beyond 25 W. It can be assumed that the slight absorption of the FBG changed the index grating, and resulted in the 1090.25-nm output.

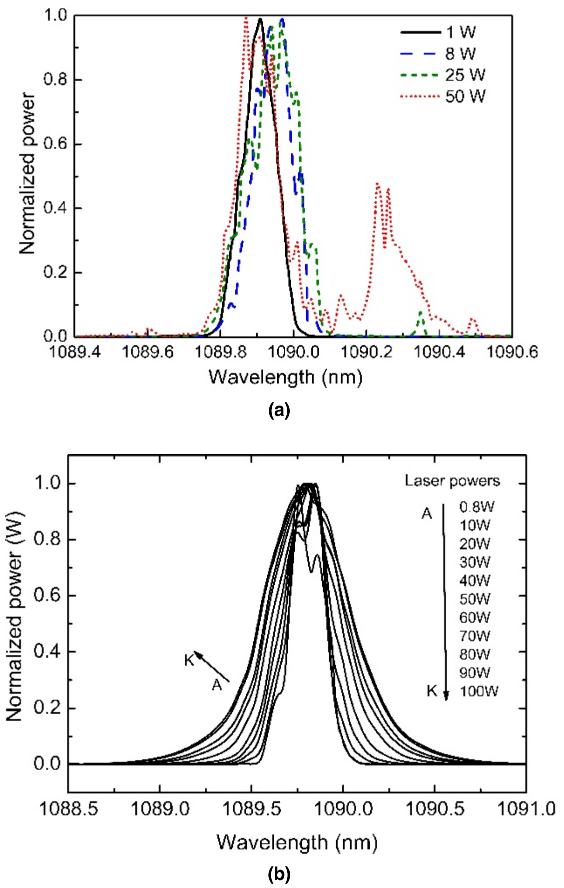

FIGURE 10. The laser linewidth of (a) the distributed pumped laser and (b) a commercial fiber laser (LIEKKI OE-Yb-L-100) on a linear scale at different signal output powers.

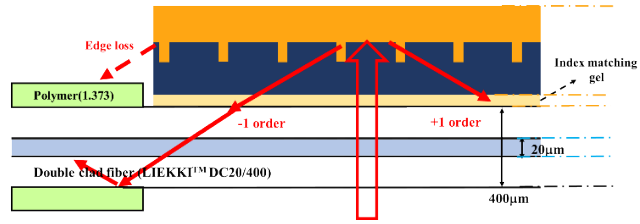

FIGURE 11. Schematic illustration of the edge loss.

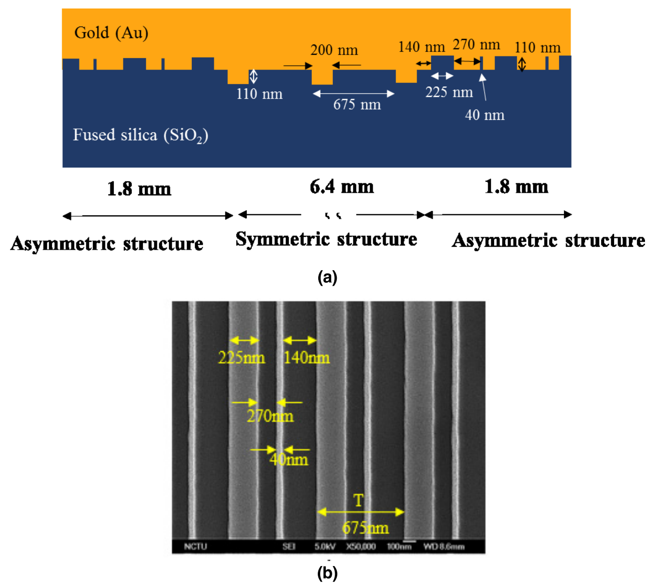

FIGURE 12. (a) Schematic of the aperiodic grating, (b) Top-view SEM photo of the asymmetric structure.

C. EDGE LOSS MITIGATION

Although coupled-out LDBS laser power of more than 120W has been successfully achieved, the coupling efficiency of 50% is still somewhat low for high-power applications. To this end, we investigated aperiodic gratings based on the genetic algorithm method to enhance the LDB coupling efficiency. As reported in [14], a coupling efficiency of a typical 1-cm-wide LDB is limited by the backward diffraction loss and edge loss. The former comes from the back reflection of the ±1st-order diffraction light on the grating coupler through the total internal reflection at the fiber cladding boundary. The edge loss is caused by the long LDB length so that the ±1st order diffraction light at both edges of the grating is lost due to the refraction at the interface between the fused silica and air [19]. To reduce the secondary diffraction loss, a short LDB length is preferred. However, due to the lack of commercial high-power LDAs with length less than 1 cm, we targeted the edge loss reduction in this research.

A schematic diagram of the edge loss is shown in Fig. 11.To eliminate the edge loss, the proposed grating was designed to reduce the −1st-order diffraction efficiency at the left edge, and +1st-order diffraction efficiency at the right edge. As reported above, we adopted the RSoft DiffractMod code to design periodic gratings. Regarding the aperiodic gratings, we added a genetic algorithm into the RSoft DiffractMod code to design the asymmetric structures at the two edges. Generally speaking, using a small unit structure helps to get the best target results. However, we only utilized the 40 nm structure in the simulation because of the fabrication limitation. The optimal design of the aperiodic

The optimal aperiodic grating design and SEM image of the asymmetric structure are shown in Fig. 12. The employed asymmetric grating structures made diffraction efficiencies on both sides significantly asymmetric. For example, in the asymmetric grating on the left, the theoretical diffraction efficiency of +1st order and −1st order increased from 45% to 64.7% and reduced from 45% to 17.8%, respectively. Accordingly, the asymmetric structure on the right was the reversed type of the asymmetric structure on the left. These two kinds of asymmetric structures were integrated with the central periodic grating section to form the aperiodic grating in Fig. 12 (a). Considering the backward diffraction loss in such a 1-cm-long LDB, the theoretical coupling efficiency of 79% is achieved, which is 11% higher than that of the fully periodic grating.

An E-beam lithography system that could fabricate structures with linewidth below 100 nm was adopted to fabricate

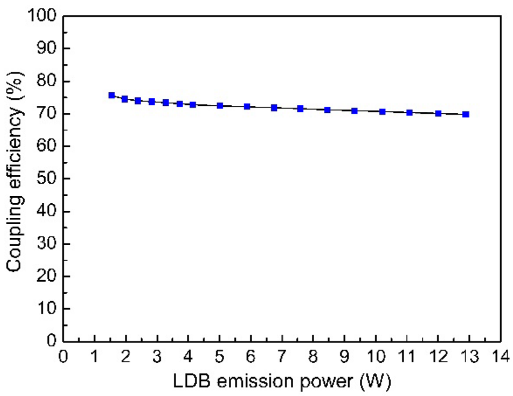

FIGURE 13. **LDB coupling efficiencies based on the aperiodic grating.**

an asymmetric grating with the 40-nm-width unit structures. In the first step, two asymmetric structures were fabricated on both ends, as shown in Fig. 12 (a). E-beam lithography combined with a secondary alignment technique was then used to fabricate the central periodic structure between the two asymmetric sections. The side-coupling efficiency into the 400 μm double-clad passive fiber based on the aperiodic gratings was then experimentally evaluated. The employed laser source was a 1-cm-long 975 nm LDB that consisted of 19 emitters with a period of 500 μm. According to the results shown in Fig. 13, the coupling efficiency of the aperiodic grating reached 70%, which was higher than that of the periodic grating. This has proved that adopting an asymmetric structure significantly mitigates the edge loss effect and, thus, results in higher coupling efficiency.

A compact, highly power scalable, distributed side-pumping scheme using the gold-embedded silica grating coupler was demonstrated for a fiber laser based on commercial double-clad fibers. At LDBS pump power of 304.4 W, a 124.6-W power was launched into 400 μm double-clad fibers with a 40.9% coupling efficiency. A side-pumped 58-W, 1090-nm Yb^{3+}-doped fiber laser with a slope efficiency of 50% was demonstrated. The narrow-linewidth output, with the spectral bandwidth of 0.11 nm maintained across the entire range of pump powers, indicates the advantage of a distributed side-pumping scheme. Power scaling in such an Yb^{3+}-doped fiber laser should be possible with more LDBs in LDBSs. The edge loss from the grating was significantly reduced with the use of aperiodic structure at the grating edges. As a result, a coupling efficiency of 70% from LDB to DCF was demonstrated. This is the highest coupling efficiency ever achieved with the 1-cm LDB. To further increase the DCF pump power, better heat dissipation capacity and minimization of the zero-order diffracted light are required. With the suitable focusing lens pair selection the side-coupling method can be used for pumping double-clad fibers with different diameters and shapes. The proposed method has a substantial potential for designing high-brightness fiber laser with higher power and better compactness than that of conventional end-pumped fiber lasers. This technique paves the way to high-power and high-quality laser sources and can take an advantage from mass production of grating couplers using the nano-imprint technique. To the best of our knowledge, this also is the first demonstration of a distributed pumped fiber laser using LDBS as the pump source.

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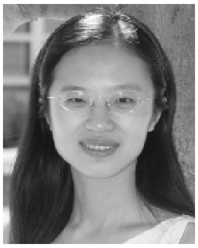

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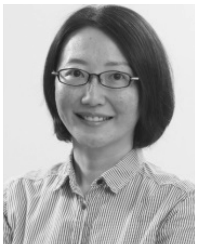

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