Improving the Quantum Efficiency of Erbium-Doped Fiber Laser by Using a Low-Loss Tipped Fiber Splicing Process

Gong-Ru Lin, *Member, IEEE,* and Gong-Cheng Lin

***Abstract*—A tipped single-mode fiber (SMF) structure is employed to reduce the fusion-splicing loss induced at the interface between SMFs and Erbium-doped fibers (EDFs). By fusing the EDF and the tipped SMF with lens-like end face at once, the optimized fusion-splicing loss of as low as $0.2 \sim 0.29$ dB is obtained. An improvement on splicing loss of up to 0.46 dB is obtained as compared to the conventional EDF/SMF fusion geometry. The effects of tapered angle and radius of curvature at the end face of tipped fiber on the optimization of fusion-splicing loss are compared. The erbium-doped fiber laser with maximum quantum efficiency of 2.75% is reported by using the proposed splicing technology.**

***Index Terms*—Erbium-doped fiber laser (EDFL), fusion-splicing loss, quantum efficiency, single-mode fiber (SMF), tipped fiber.**

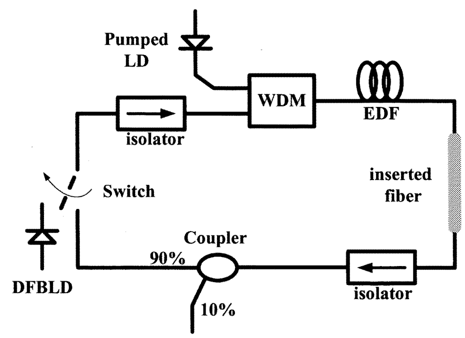

Fig. 1. Setup of EDFL system with different fibers inserted between the EDF and the SMF-pigtailed isolator.

I. Introduction

ERBIUM-DOPED fiber amplifiers (EDFAs) and lasers (EDFLs) have recently emerged as novel all-fiber-based optical modules which cause considerable interests in such as *in situ* amplification, reconstruction, and carrying of high-bit-rate optical signals transmitted in fiber-optic systems. One of the problems of greatest concern in constructing EDFA or EDFL is the large splicing loss of $1.9 \sim 2.2$ dB introduced during the fusion-splicing process [1] that results from different mode-field distributions (MFDs) between EDF and single-mode fibers (SMFs). The improvement on the overall quantum efficiency of EDFL, η (defined as the ratio of output power to input power at 980 nm), is strictly affected by such losses happening at the interfaces of the fiber components with different structure or core diameters used in the EDFL cavity. Previously, the most optimized η ever obtained from a standard EDFL system with 10% output geometry (as shown in Fig. 1) ranged from $0.33\% \sim 1.2\%$. The adjustment on the tooling parameters of splicing process are, thus, important to reduce serious loss caused at the fusion interface of EDF and SMF with different core diameters and shapes. However, the multifusion processes with fine-tuned fusion currents are required to obtain low splicing loss for fusion splicing of different fibers. In addition, suitable arc power and reduced fusion time are also helpful in achieving lower splicing loss. To simplify the fusion-splicing procedure between different fibers, versatile local MFD transforming schemes have also been proposed, which efficiently reduces the fusion-splicing loss between EDF and SMF to 0.5 dB[2]. For example, several types of tapered-fiber splicing methods by stretching [3] or drawing [4] the fusion-spliced portion, or by diffusing dopants [5] into the SMF to expand the core region have been addressed. In this letter, we investigate different fusing geometries for enhancing the coupling efficiency between EDF and SMF by inserting fibers with different core diameters. In addition, we propose for the first time the improvement of overall quantum efficiency of the EDFL by fusing the EDF with a tipped SMF of gradually tapered core–cladding diameter and lens-like end face. The maximum output power, the quantum efficiency, and the fusion-splicing loss of the EDFL with different fusing schemes under low pumping condition are measured and compared. The fusion-splicing losses of the geometries using SMFs with different tapered angles are also discussed.

II. Experimental

The setup of the EDFL system for measuring the coupling efficiency of EDF/SMF fusing point is shown in Fig. 1. The EDFL consists of a unidirectional ring cavity, which is constructed by using a 6-m-long EDF (Lucent R37005) as the gain medium, a pumped laser diode of 75-mW maximum output power operated at $\lambda = 976.1$ nm, a 980/1550 wavelength-division-multiplexed (WDM) coupler, a 10% output coupler, and two polarization-independent isolators. With an optical switch, a distributed-feedback laser diode (DFBLD) is employed to determine the fusion-splicing loss between the EDF and different

Manuscript received October 15, 2002; revised May 19, 2003. This work was supported in part by the National Science Council (NSC) under Grant NSC90-2215-E-009-039.

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Digital Object Identifier 10.1109/LPT.2003.816662

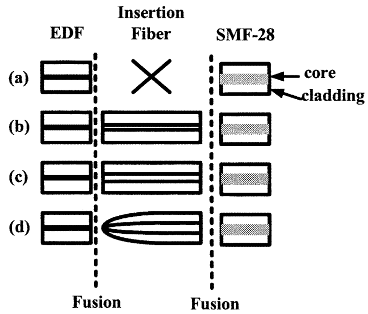

Fig. 2. Fusion-splicing geometries between EDF and SMF with buffered fibers for MFD transformation. (a) Without any inserted fiber. (b) Inserting a 5.5-μm core fiber. (c) Inserting a 6.6-μm core fiber. (d) Inserting a tipped SMF.

segmented fibers. The schematic diagrams of the fusion geometries using different buffered fiber structures are illustrated in Fig. 2. Different segmented fibers with versatile core diameters or a tipped SMF with a lens-like end face are inserted between the EDF and the isolator (with pigtailed SMF) to reduce the fusion-splicing loss. In Fig. 2(a), the EDF and SMF are directly fusion-spliced by three times without any buffered fiber structure. In other fusing schemes depicted in Fig. 2(b) and (c), a 10-cm-long buffered fiber with core diameters of 5.5 and 6.6 μm are fused once between the EDF and SMF, respectively. In Fig. 2(d), a tipped-SMF structure with tapered core–cladding diameter and lens-like end face fabricated at one side of the isolator is inserted to fusion-splice with the EDF. The manufacturing module for the tipped-SMF structure is slightly modified from a standard fiber fusion splicer (RXS, X-76). The tipped SMF is performed by first peeling off the protecting plastic cover, cleaning the fiber, and putting the fiber on the V-shaped groove of the fusion splicer. Subsequently, the SMF was arced three times by the 1-s fusion process with a current of 12.5 mA. To adjust the tapered angle and radius of curvature at the end face of the tipped SMF, either a 20- or a 40-g counterpoise was concurrently added at one end to pull the fiber when preceding the fusion-splicing process.

III. Results and Discussions

In experiment, two different tipped SMFs were fabricated by pulling the SMFs with 20- and 40-g counterpoises during fabrication process. The microscopic pictures of the tipped SMFs prepared at different conditions were taken by using scanning electron microscope [(SEM) JSM-5600] are shown in Fig. 3. It is found that the tipped SMF fabricated with heavier pulling counterpoise exhibits not only a shorter tapered region, but also a smaller radius of curvature at the lens-like end face. Subsequently, the fusion splicing of EDF and SMF with different cores or tipped enfaces were performed by setting the fusion splicer at manual scan-alignment mode, which was chosen to prevent the misalignment that happened between fibers with different structures and preserve the maximum coupling efficiency. The EDFL was turned on and the X, Y, and Z axes of the fusion splicer were fine tuned to obtain a maximum output power of the EDFL before each fusion process proceeded. The fusing current and time for all geometries shown in Fig. 2 are 14.5 mA and 3.5 s, respectively. By seeding a DFBLD with 1.8-dBm power into the open-loop EDFA (see Fig. 1) with different fusion-

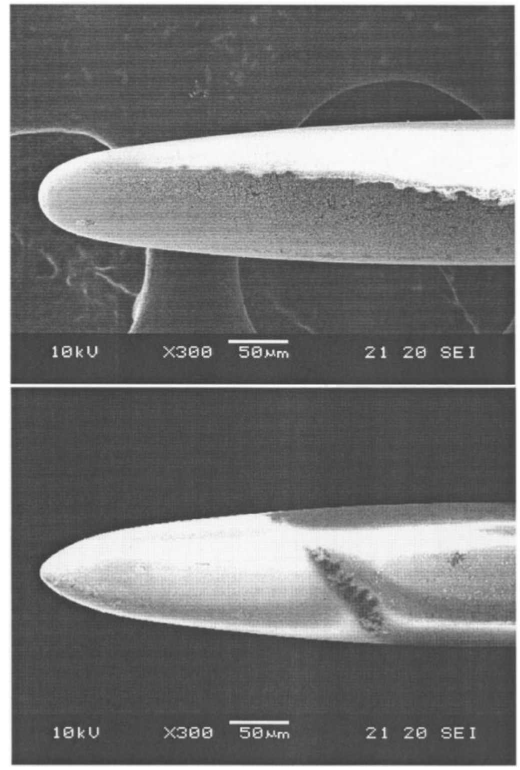

Fig. 3. SEM photographs of the tapped SMFs pulled by use of 20-g (top) and 40-g (bottom) counterpoises.

TABLE I
The Optical Powers Sequentially Measured at the Output Ends of Different Fusion-Spliced Modules in the EDFA and Their Evaluated Losses. EDF/6.6/SMF: Fusion a Buffered Fiber With 6.6-μm Core Between EDF and SMF; Tip1-SMF: the Tipped SMF Using 20-g Counterpoise; Tip2-SMF: the Tipped SMF Fabricated Using 40-g Counterpoise

Output / Geometry	DFBLD mW	WDM mW	EDF mW	Fused mW	Loss dB
EDF/SMF	1.51	1	9.61	8.26	0.66
EDF/6.6/SMF	1.51	1	9.83	8.97	0.4
EDF/Tip1-SMF	1.51	1	10.55	9.87	0.29
EDF/Tip2-SMF	1.51	1	11	10.45	0.2

spliced modules shown in Fig. 2, the optical powers sequentially measured at each output port of the DFBLD, the WDM coupler, the EDF, and the fusion-spliced fiber are listed in Table I. The splicing loss at the interface of EDF/tipped SMF is extremely low (-0.2 dB/port) as compared to that of EDF/SMF (-0.66 dB/port).

Subsequently, the performances of EDFL constructed by different fusion-splicing geometries are characterized. It is seen that without the use of any buffered fiber of different core diameter as the MFD transforming geometry, a much better overall quantum efficiency of 1.34% with our EDFL as compared to previous reports is obtained. The calculated two-port fusion-splicing loss (including input and output interfaces of EDF) is about 1.5 ± 0.2 dB (pumping power dependent). In contrast, the EDFL systems with buffered fibers of core diameters of 5.5- and 6.6-μm fusion splicing between the EDF and the SMF at the same process condition are found to exhibit higher quantum efficiencies and lower fusion-splicing

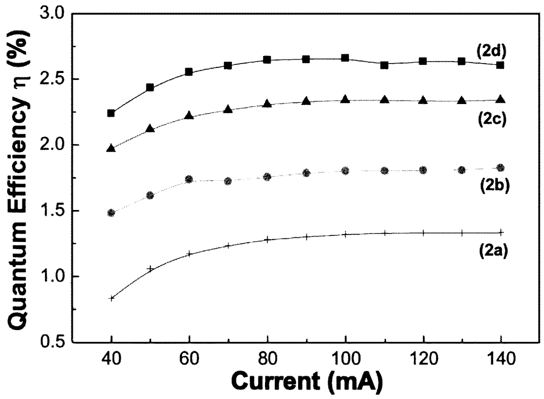

Fig. 4. Quantum efficiencies of the EDFL with different fusion-splicing geometries between the EDF and SMF shown in Fig. 2.

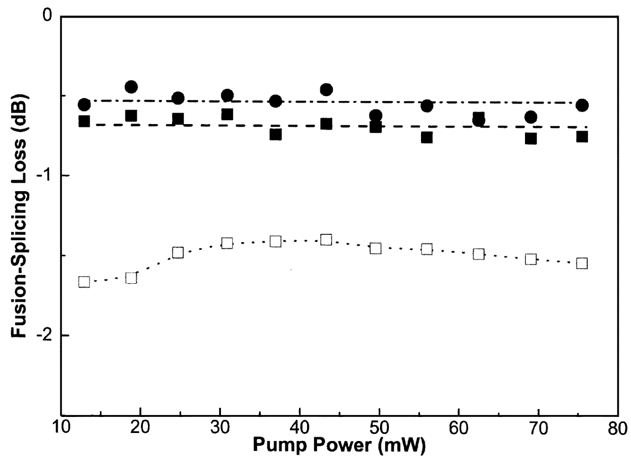

Fig. 5. Two-port fusion-splicing loss as a function of pumping power of EDFL at the interfaces between EDF and the typical SMF (hollow square), the tipped SMF fabricated with 20- (solid square) or 40-g (solid circle) pulling counterpoises.

losses than the same system but with a directly fusion-spliced EDF/SMF interface. The maximum output powers of the EDFL with different MFD transforming geometries shown in Fig. 2(a)–(d) are 1.01, 1.38, 1.77, and 2.0 mW under a pumping level of 75.5 mW, respectively. Obviously, the tipped-SMF fused EDFL geometry exhibits a highest output level as compared to others under the same pumping level. Note that only one-time arcing procedure is employed for fusion splicing the tipped SMF and EDF. The overall quantum efficiency of the EDFL operated at different pumping levels is shown in Fig. 4. A slightly saturated trend of the efficiency is found when operating at high pumping powers. Nonetheless, the EDFL system with tapered fiber tip as an MFD transforming structure between EDF and SMF has shown to exhibit the largest power gain as well as the best coupling efficiency. The maximum ηs of the EDFLs using buffered or tipped fiber as the MFD transforming geometries shown in Fig. 2(b)–(d) are 1.75%, 2.25%, and 2.75%, which have already been improved by 1.4, 1.7, and >2 times on the coupling efficiency than that of the same EDFL with the directly fused EDF/SMF interface shown in Fig. 2(a). This result has corroborated the better MFD transforming performance of the simple tipped-SMF structure, which greatly simplifies the conventional arcing process and improves the coupling efficiency between the fusion-spliced EDF and SMF. The two-port fusion-splicing loss of the EDF/tipped-SMF interface at different pumping powers shown in Fig. 5 are ranging from 0.7 ± 0.1 dB, which is significantly better than that of the typical EDF/SMF interface (improving by $0.6 \sim 1$ dB). The tipped SMF fabricated by heavier pulling counterpoise could further improve the fusion-splicing loss by at least 0.2 dB for the EDFL at higher pumping levels. The effect of the smaller diameter at the tapered end face of the tipped SMF on the fusion-splicing loss is believed to be more pronounced than the effect of smaller radius of curvature.

In conclusion, we have studied the performance of a tipped-SMF structure in reducing the fusion-splicing loss induced at the interface between SMFs and EDFs. Different fusing schemes by using buffered fibers with different core diameters or tipped-SMF structure between EDF and SMF to improve the quantum efficiency are compared. Among the proposed different fusing schemes, the system with a tapered fiber tip as a buffered fusing structure is found to exhibit the largest power gain as well as the best coupling efficiency. By arcing the EDF and the tipped SMF with the lens-like end face at once, the optimized fusion-splicing loss of as low as $0.2 \sim 0.29$ dB is obtained. The proposed technique greatly improves the splicing loss of EDF/SMF geometry by at least 0.46 dB. The performances of two tipped SMFs with different tapered lengths, tapered diameters, and radius of curvature at the end faces are compared. The effect of the smaller diameter at the tapered end face of the tipped SMF on the fusion-splicing loss is more pronounced. The maximum output power of the EDFL with the EDF/SMF interface fusing with buffered and tipped fibers are 1.8 and 2.0 mW under a pumping power of 75.5 mW. The EDFL with maximum quantum efficiency of 2.75% is reported. An over two-time improvement on the quantum efficiency of the EDFL is achieved by using the proposed splicing technology.

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