Chapter 1

Self-pulsing Dynamics in Yb-doped Fiber Lasers

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Abstract

There is worldwide considerable interest in the study and development of high-power Yb-doped continuous wave (CW) and pulsed fiber lasers for various material processing applications. Although it appears to be trivial to generate high-power CW output from Yb-doped CW fiber lasers by pumping with high-power CW laser diodes; however, it is not so easy to generate truly CW output without amplitude modulations due to self-pulsing phenomenon. The observation of random self-pulses overriding CW output has been reported by several authors. These random self-pulses may have very high peak power to cause catastrophic damage of fiber laser components and thereby inhibit generation of high-power CW output. This chapter describes self-pulsing dynamics and its elimination in different Yb-doped CW fiber laser configurations.

Keywords: Yb-doped fiber, self-pulsing, saturable absorption

1. Introduction

High-power Yb-doped double-clad fiber lasers have recently attracted considerable attention due to its advantages such as single-mode operation, all-fiber integration, high efficiency, compactness, no misalignment sensitivity, robustness, and efficient heat dissipation due to large surface area to volume ratio.[1,2] Yb-doped fibers provide wide absorption band in the range of ~800–1064 nm, and it can provide lasing in the range of ~974–980 and ~1010–1160 nm. Thus, Yb-doped fiber lasers are unique laser sources for a wide range of applications. Hanna et al. reported tuning range from 1010 to 1162 nm with a total span of 152 nm.[3] In view of this, there has been a growing interest in high-power Yb-doped fiber lasers as a potential replacement for bulk solid-state lasers in many applications. There are reports on the development of up to 2 kW of single-transverse-mode fiber laser and its commercial availability.[1] However, its efficiency and configuration is not reported in the literature. Record brightness from Yb-doped fiber laser with output power of up to 10 kW at 1070 nm of output wavelength has also been reported by IPG Photonics.[1] This laser is the most intense CW laser of any kind with maintenance-free operation, a compact footprint, and ultra-long operational life. Such an intense laser can perform a variety of material processing and defense applications. For the generation of very high output power from fiber lasers, either only oscillator or master oscillator power amplifier (MOPA) configurations are normally used. However, the output power from Yb-doped fiber lasers is mainly limited by nonlinearities, thermal effects, fiber fuse effect, and optical damage of fiber-optic components used in oscillator or MOPA configuration.[4]

At a first glance, it is normally felt that it is an easy task to generate CW output from Yb-doped fiber lasers, but it is not so easy to achieve purely CW output having highly stable output without modulations as achieved in conventional lamp-pumped or diode-pumped solid-state lasers. It is normally expected to achieve a CW output from fiber lasers under CW pumping conditions. However, in several CW pumped rare-earth-doped fiber lasers with different resonator configurations and pumping geometries, modulations in the output and self-pulsations over-riding CW level has been reported.[5–13] Two types of self-pulsations have been reported in fiber lasers, they are as follows: (a) sustained self-pulsing (SSP) and (b) self-mode locking (SML).[7] In case of SSP, emission of high-intensity pulses at irregular intervals is observed, whereas in the case of SML, pulse spiking in the output or laser signal modulation is observed at the round trip time of the resonator cavity. Several possible origins have been suggested for self-pulsing in the literature. These include re-absorption of laser signal in the weakly pumped or un-pumped section of the rare-earth-doped fiber,[11–14] ion-pairing acting as a saturable absorber,[8–10] relaxation oscillations due to inversion in the gain medium and population of photons in the cavity,[10] resonator steady-state conditions and Q-factor of the cavity,[5,15] interaction between laser signal and population inversion,[16] pump noise as the source of self-pulsing.[17,18] Further, cascaded stimulated Brillouin scattering (SBS), distributed Rayleigh scattering, and the set of other nonlinear effects (SRS (stimulated Raman scattering); SPM (self-phase modulation); XPM (cross-phase modulation); and FWM (four wave mixing)) [19–22] have also been suggested as the sources of self-modulation and self-pulsing in different rare-earth-doped fiber lasers. Control on self-pulsing to achieve narrow pulses at regular interval and with enhanced Q-switching has also been reported.[23] Substantial effort has been put up by several authors to reduce self-pulsing. Suppression of self-pulsing has been carried out by using a low transmission output coupler giving a high Q-cavity,[5] using unidirectional fiber ring cavity,[5,7,24] increasing round trip time in the cavity by splicing a long section of matched passive fiber and thereby changing the relaxation oscillation dynamics,[25] uniform bidirectional pumping,[26] suppressing relaxation oscillation frequency component,[27] preventing rapid depletion of gain by resonant pumping near the lasing wavelength and thereby minimizing relaxation oscillations,[28,29] electronic feedback to the pump laser for shifting the gain and its phase.[30] In addition, the use of the narrow passband of a $\lambda/4$-shifted fiber Bragg grating (FBG) structure in a ring cavity to limit the number of longitudinal cavity modes [31] and the use of fast saturable gain of a semiconductor optical amplifier within the fiber laser resonator [32] have also been reported to suppress self-pulsing.

2. Effect of laser resonator on self-pulsing dynamics

The experimental setup to show the effect of laser resonator on self-pulsing dynamics consisted of a Yb-doped double-clad fiber having a core diameter of 10 μm and an inner-clad diameter of 400 μm with core and inner-clad numerical aperture (NA) of 0.075 and 0.46, respectively. This Yb-doped fiber had clad-pump absorption of 0.8 dB/m at 975 nm, and it had an octagonal inner-clad geometry to avoid excitation of skew modes. A fiber-coupled laser diode of 20 W output power and center wavelength of 975 nm was used to pump 18 m length of the above-mentioned Yb-doped fiber. The Yb-doped fiber was perpendicularly cleaved at both the ends to sustain higher damage thresholds. Study of three different Fabry–Perot resonator configurations as shown in Figures 1(a), 1(b), and 1(c) was carried out.[15] Figure 1(a) shows the forward-pumping configuration with high finesse in which a dichroic mirror with ~100% reflectivity at signal wavelength and high transmission at pump wavelength is kept in between the two lenses used for coupling pump light in to the Yb-doped fiber and the cleaved end with ~4% Fresnel reflection at the farther fiber end of the doped fiber acts as the output coupler. Figure 1(b) shows the backward-pumping configuration with high finesse in which two dichroic mirrors have been used, one for ~ 100% feedback of the signal and another at an angle of 45° for taking laser output from pump input end of fiber. In this case, the perpendicularly cleaved pump input end of the doped fiber with ~4% Fresnel reflection for laser signal acts as the output coupler. Figure 1(c) shows the low-finesse fiber laser resonator configuration; in this case, the cleaved ends with ~4% Fresnel reflection from both the fiber ends act as Fabry–Perot cavity mirrors. The dichroic mirrors used in these configurations are highly transmitting in the range of 960–980 nm and highly reflecting (≈98%) in the wavelength range of 1064–1140 nm. Output power was measured after filtering out the unabsorbed pump power using a thermal power meter. Maximum output power of 10.75 W was achieved with a slope efficiency of ~73% in the backward-pumping configuration at an input pump power of 17.2 W.

However, in the case of low-finesse cavity configuration of Figure 1(c), it was observed that the output power from both the ends ceases to increase beyond 1.8 W and starts fluctuating due to appearance of strong random self-pulsing over-riding CW output. With further increase in the pump power, an increase in the fluctuation about the average output power was observed and peak power of these random pulses were also found to increase. At an input pump power of 8 W, Figure 2(a) shows the observed random self-pulsing, and Figure 2(b) shows the expanded view of one of the random self-pulses with observed pulse duration of less than 25 ns. As the pulses are random in time domain with variation in frequency duration, and their peak powers are also not constant, the measured average power keeps fluctuating.

There is report on the occurrence of random self-pulsing in a V-groove pumping configuration in the case of "bad cavity" (R_1=100%, R_2=4% or R_1=4% and R_2=4%) and no such random self-pulsing in the case of "good cavity"(R_1=100%, R_2=80%) by Hideur et al.[5] They proposed that random self-pulsing behavior in the case of bad cavity may arise due to re-absorption of the laser signal in the un-pumped part of the fiber, and the occurrence of SRS and SBS, whereas in the case of a good cavity, the device behaves as a laser with saturable absorber and Brillouin and Raman effects do not occur.[11,12] However, it is clear that intracavity intensity in the case

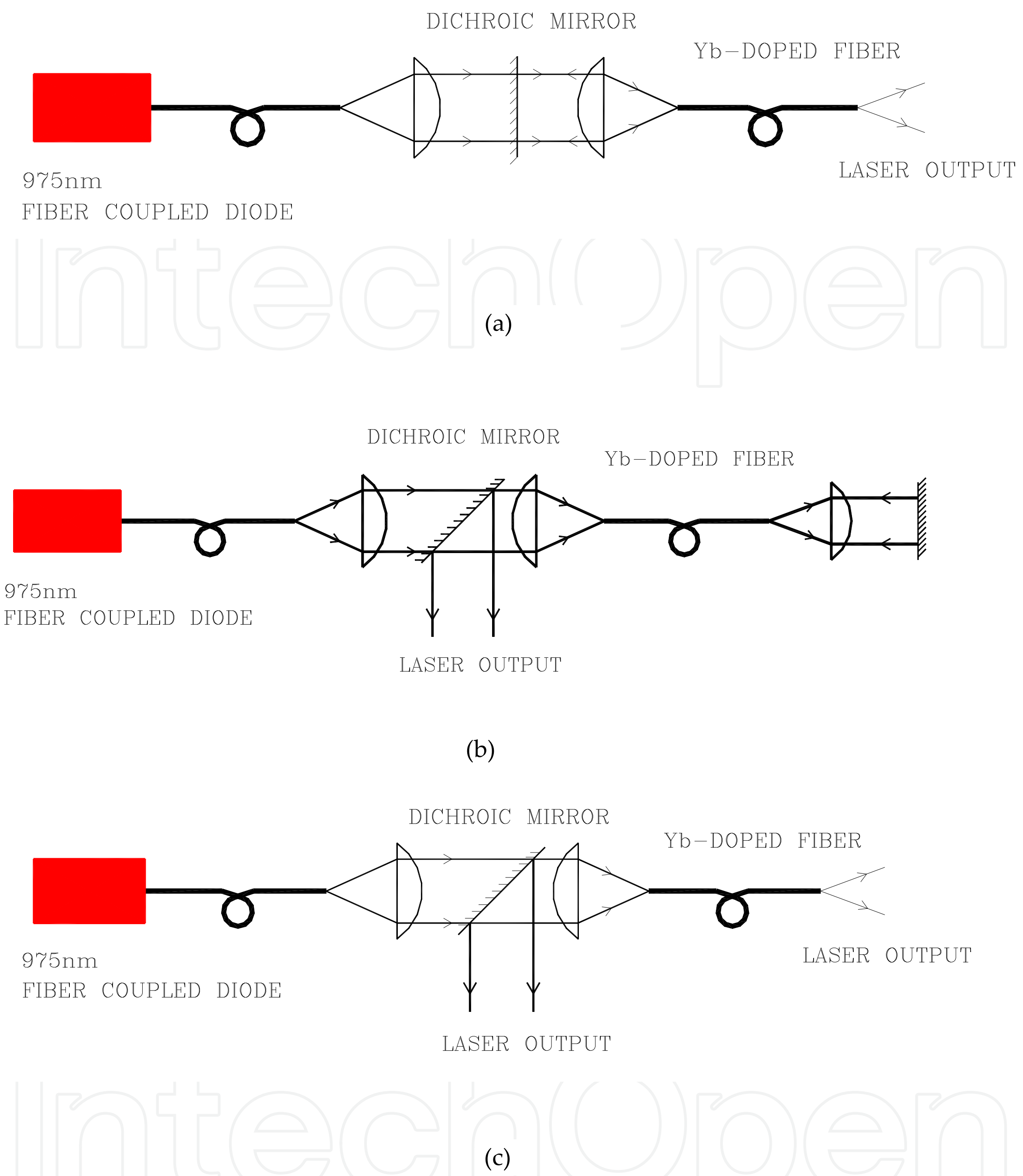

Figure 1. (a) High-finesse forward-pumping configuration with output power taken from the farther end of Yb-doped fiber, (b) high-finesse backward-pumping configuration with output power taken from the pumping end of the Yb-doped fiber using the 45° tilted dichroic mirror, and (c) low-finesse resonator configuration with laser output from both the ends.[15]

of a good-cavity will be much larger as compared to that in the case of a bad-cavity; therefore, the nonlinear SRS and SBS processes should occur at a much earlier value in the case of a good-cavity than in a bad-cavity, which contradicts their proposal. It has been shown by Fotiadi et al.[21] that mechanism of self-pulsing involves distributed backscattering in the form of Rayleigh scattering (RS) and SBS. At the beginning of the cycle, the pump provides a buildup

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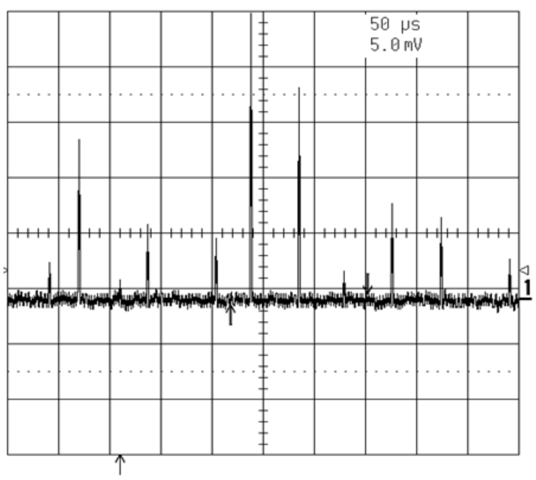
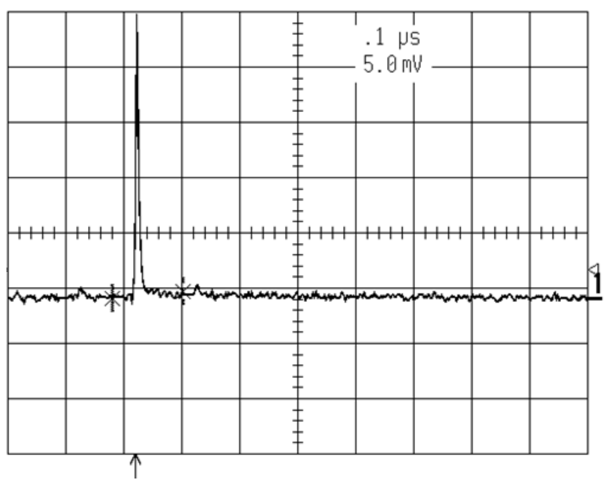
of the population inversion in the gain medium and the gain increases gradually. However, CW lasing is completely inhibited due to the suppression of feedback by the imposed angle at the fiber ends and feedback into the cavity is provided mainly by the distributed RS and SBS that leads to generation of gigantic irregular random self-pulses. In cases of good-cavity or high-finesse cavity and bad-cavity or low-finesse cavity, where feedback is not suppressed by angle cleaving of fiber ends and dominant feedback is through fiber-end facets or feedback mirrors, self-pulsing behavior is completely different.

We noted the threshold powers for occurrence of random self-pulsing in three different configurations for the investigation of random self-pulsing behavior in low- and high-finesse cavities. In cases of high-finesse resonator configurations R_1=98%, R_2=4% (forward pumping) and R_1=98%, R_2=80% (good-cavity), the random self-pulsing thresholds were found to be 6.2 and 12.7 W, respectively, whereas in the case of low-finesse resonator configuration (R_1=4%, R_2=4%), the self-pulsing threshold was found to be 2.8 W. Further, in the case of forward-pumping configuration, the output power was found to vary linearly with input pump power and the self-pulsing effect was very weak. Whereas in the case of low-finesse resonator configuration, output started fluctuating beyond 1.8 W and self-pulsing was found to be very strong. The higher threshold for occurrence of random self-pulsing in case of good-cavity and lower thresholds for bad-cavity configurations show that mirror reflectivities also play an important role in the onset of random self-pulsing behavior. Occurrence of a peak in the gain vs length curve could cause any pump-induced noise or distributed backscattered noise in the form of RS and SBS to build up and emit in the form of strong random pulses. Thus, in order to avoid random self-pulsing in CW fiber lasers, gain peaking along the fiber length should be avoided by uniform pumping along the fiber length with dual end pumping or multipoint pumping or by choosing appropriate cavity mirror reflectivities.



(a)



(b)

Figure 2. (a) Output of the fiber laser, showing random self-pulses in the case of low-finesse cavity of Figure 1(c), for an input pump power of 8 W, and (b) an expanded oscilloscope trace of one of the random self-pulses from Yb-doped fiber laser.[15]

Figure 3 shows average output spectrum in the case of low-finesse cavity configuration of Figure 1(c) before and after the onset of random self-pulsing behavior. This spectrum shows the presence of nonlinear SRS effect in the presence of random self-pulsing with first-order Stokes peak at a wavelength separation of 50 nm from the laser line. However, we could not confirm the occurrence of SBS due to smaller SBS shift and limited resolution of the optical spectrum analyzer.

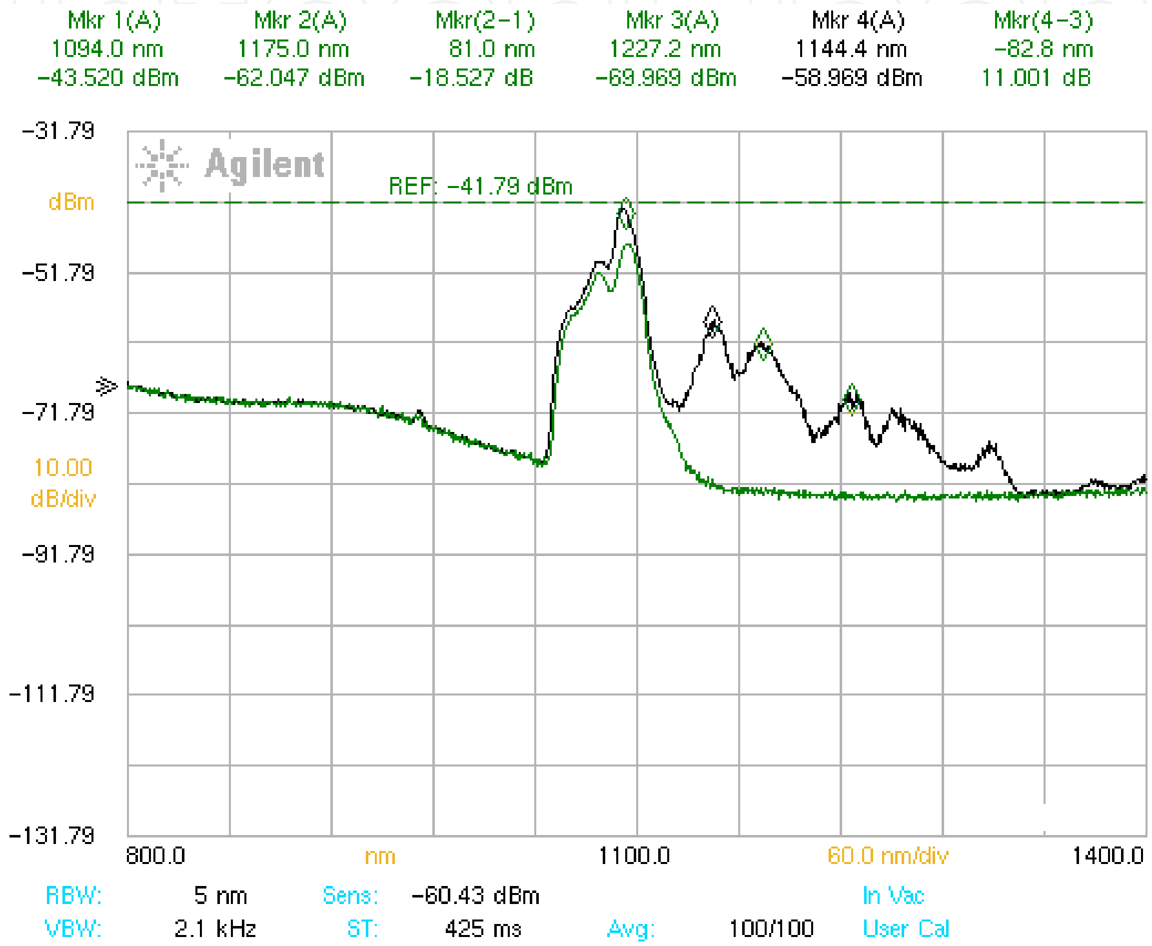


Figure 3. Output spectrum in case of low-finesse cavity of Figure 1(c); the lower trace shows spectrum before onset of random self-pulsing at 2.5 W of input pump power, and the upper trace shows output spectrum after onset of strong random self-pulsing at 8 W of input pump power.[15]

3. Effect of fiber length and laser linewidth on self-pulsing dynamics

Length of the doped fiber used for the fiber laser setup and the laser linewidth also plays an important role in self-pulsing dynamics. Root cause for the onset of self-pulsing is relaxation oscillation at low pump powers and saturable absorption along the weakly pumped portion of the fiber at the farther end, whereas nonlinear SRS and SBS effects are responsible for an increase in the peak power of these relaxation oscillation pulses. In fiber lasers with single-end

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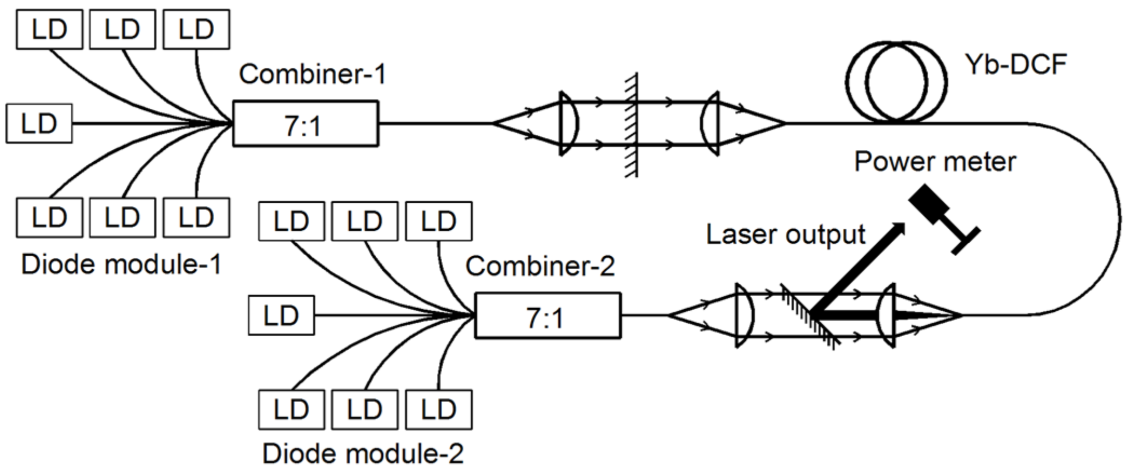
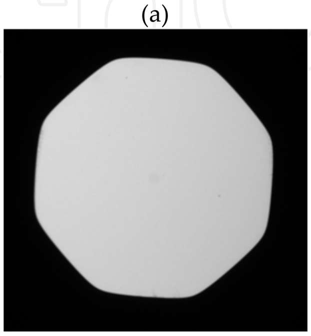
or double-end pumping with wide- or narrow laser linewidths, most of the pump power is absorbed near the pump input end of the doped fiber; hence, there is always a weakly pumped region at the farther end of the doped fiber in the case of single-end pumping configuration and at the middle portion of the doped fiber in the case of double-end pumping configuration. The presence of weakly pumped region is responsible for signal re-absorption along the fiber length, and thereby causes self-pulsation due to "saturable absorption effect" as in the case of conventional passively Q-switched lasers. However, due to the "distributed nature" of saturable absorption of signal along the fiber length, self-pulsing is random in nature with variations in the frequency and time duration of self-pulses. With increase in input pump power, there is an increase in the frequency of these self-pulses, which is clear from the observed sequence of self-pulses under different resonator and pump conditions, and is a typical characteristic of passively Q-switched lasers. Gain uniformity increases with further increase in pump power and there is a corresponding reduction in saturable absorption of the signal along the fiber due to the absence of weakly pumped region, which eliminates self-pulsation at higher pump inputs. Depending on the signal intensity and excited state absorption of signal in the doped fiber, passively mode-locked pulses with a characteristic separation equal to the round-trip time may also appear in the self-pulse envelope, as in conventional bulk "passively Q-switched lasers having simultaneous mode locking". If the doped fiber length is long and laser linewidth is also narrow, it may happen that SBS threshold is reached, which will further enhance self-pulses. If the fiber length is long but the linewidth is not narrow, it may result in generation of SRS and thereby enhance self-pulses.[33–36]

4. Self-pulsing dynamics of high-power Yb-doped fiber laser with bulk mirror resonator

The experimental setup of Yb-doped fiber laser with bulk mirror resonator consisted of a large mode area Yb-doped double-clad fiber with a core diameter of 20 μm and an inner-clad diameter of 400 μm. The outer clad is made of fluoroacrylate polymer and had a diameter of 550 μm. Core and inner cladding NA's are 0.060 and 0.46, respectively. Inner-clad pump absorption at 975 nm is 1.7 dB/m. Thus, a length of 15 m of Yb-doped fiber was selected to have an efficient pump absorption of ~25 dB with minimum leakage of the input pump beam. An octagonal shape inner cladding of this fiber avoids excitation of skew modes. Yb-doped fiber ends were cleaved perpendicularly and coiling of the active fiber was done on a metallic mandrel to remove heat load from it. Fourteen number of laser diodes at 975 nm with an output power of 30 W and pigtail fiber core diameter of 200 μm and 0.22 NA were used to pump from both the ends of the active fiber using 7:1 multimode fiber-optic pump combiners. All the diodes were maintained at an operating temperature of 25 °C for the entire range of its output power using water-cooled heat sinks for mounting. Fiber output of seven such diodes were fusion-spliced individually with seven matched pump input ports of multimode fiber-optic pump combiner using GPX-3400 fusion splicing workstation from M/s Vytran. All the splice joints were optimized and a maximum transmission of ~86% was achieved. A cumulative loss of 14% is due to mismatch between fibers of diode pigtail and pump combiner fiber input ports along with insertion loss from each input port of fiber-optic pump combiner. Pump combiner output port had a core diameter of 400 μm and an NA of 0.46. Two such diode pump modules were made as shown in Figure 4(a), and these were used to pump from both ends of the active Yb-doped double-clad fiber using two 7:1 pump combiners. Pump beam at 975 nm from output port of each pump combiner was initially collimated using a 20 mm focal length lens, and then, it was imaged at the active fiber ends using another 20 mm focal length lens. Temperature-controlled metallic V-grooves were used to hold the ends of the Yb-doped fiber to prevent any possible thermal damage to the gain fiber coating by the heat generated in the gain fiber due to nonradiative emission processes or by means of any over filled pump or signal power. In order to have signal feedback in laser oscillator, a dichroic mirror with high reflectivity (HR) of ~100% in broadband from 1040 to 1100 nm for normal incidence and high transmission (HT) at 975 nm has been placed at one end of the Yb-doped double-clad fiber between the two lenses. Resonator mirrors are formed by this mirror along with the other cleaved end of the Yb-doped fiber providing 4% Fresnel reflection. Another dichroic mirror with HR in a broadband from 1040 to 1100 nm at 25° angle of incidence and HT at 975 nm has been placed between the two lenses to have laser output from the resonator. Figure 4(a) shows a schematic of the experimental setup, and Figure 4(b) shows an image of Yb-doped double-clad fiber-end face having octagonal inner cladding using a microscope.



(a)



(b)

Figure 4. (a) A schematic view of 165 W of Yb-doped CW fiber laser, and (b) an image of Yb-doped double-clad fiber-end face with octagonal inner cladding using microscope.

From this experimental setup, an output power of 165 W was achieved at the combined maximum input pump power of 316 W from both the ends with a slope efficiency of 56.5% and an optical-to-optical conversion efficiency of 52%. Experimentally measured value of threshold pump power was 20 W. Theoretical estimate of threshold pump power was 9.5 W, which is much lower than the measured value. This is due to the fact that at lower pump powers, input pump wavelength was near to 968 nm, which is far away from the peak pump absorption wavelength of 976 nm. Using a compatible passive fiber in the same setup, pump coupling efficiency from the output of pump combiner to the active fiber was measured to be 65%, which is very less and can be further improved to reduce pump power losses and achieve higher conversion efficiencies. Taking into account, the pump coupling losses, optical-to-optical conversion efficiency improves to a value of 80.5%, which is close to the maximum reported figure of 83% for high-power Yb-doped fiber lasers by Jeong et al.[2] Variation of output pump power as a function of input pump power is shown in Figure 5. It shows that there is linear variation in output power with respect to an increase in input pump power, and there is no saturation in the output laser power even at the maximum value of input pump power. This shows that laser output power is limited only by the input pump power. Figure 6 shows recorded output spectrum at the maximum laser output power of 165 W. The laser output spectrum is peaked at 1079.7 nm with spread from 1064.1 to 1100.1 nm and full width half maximum linewidth of ~7 nm. There is another peak near 975 nm in the output spectrum, which shows pump wavelength peak.[37]

Laser output from the Yb-doped fiber is emitted from the core of 20 μm diameter in a full-cone angle of 120 mrad. V-number of the active fiber is 3.5, which suggests that it may provide guidance of a total of six number of fiber modes. Thus, fiber laser output may be slightly multimoded. But, the Yb-doped fiber was coiled on a mandrel of 150 mm diameter to increase losses for higher order modes and thereby ensure single-mode operation. A laser beam profiler from M/s Spiricon was used to measure laser output beam profile and measured value of M^2 was found to be ~1.04, which shows a nearly diffraction-limited laser output beam. During experiments, it was found that relaxation oscillations override the CW signal output near threshold, and consequently, generate high peak power random self-pulses with pulse duration of the order of a few nanoseconds, which damages fiber ends or any other fiber laser component. This damage of fiber components is irreversible. Thus, it is of utmost importance to remove random self-pulsing, before proceeding for the generation of high-power output from Yb-doped fiber lasers. Fiber ends are also prone to damage by dust particles due to emission of high power from very small core area and the presence of high-power density at the fiber-end faces. Hence, it is also important to protect fiber ends by means of fiber end caps. It was found that if the mirrors are not aligned properly, it introduces higher loss in the resonator and results in the generation of self-pulses, which may even damage the mirror coatings due to high peak power density of self-pulses. Figure 7 shows generation of high peak power random self-pulses when the resonator mirrors are slightly misaligned. However, if the mirrors are aligned properly to generate maximum output power, there are no self-pulses in the output. Thus, intracavity loss has to be minimized to prevent generation of random self-pulses.

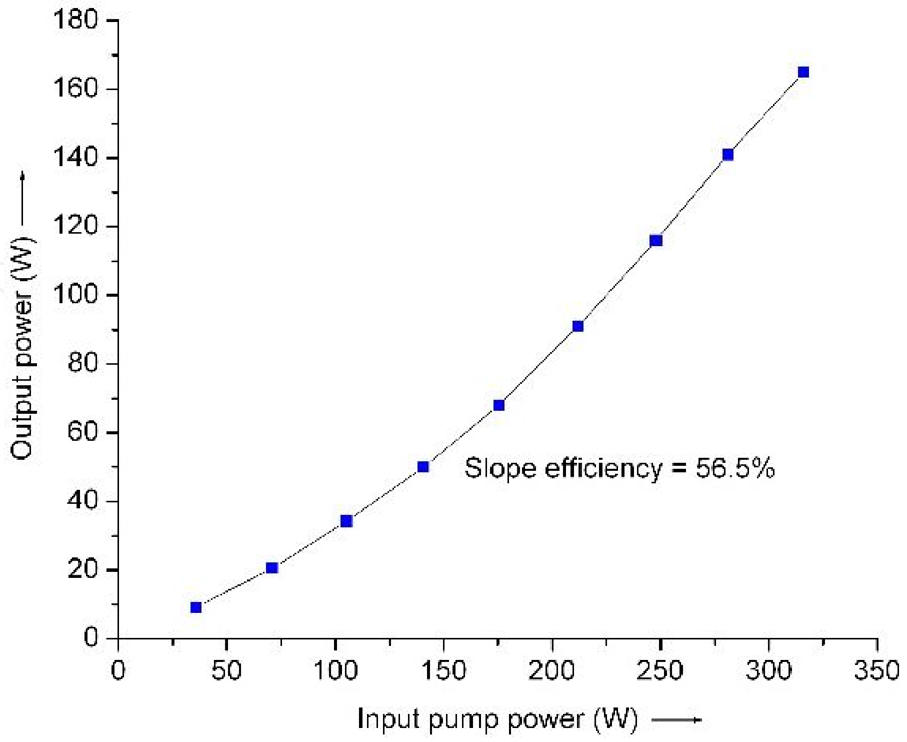


Figure 5. Variation of laser output power as a function of input pump power.

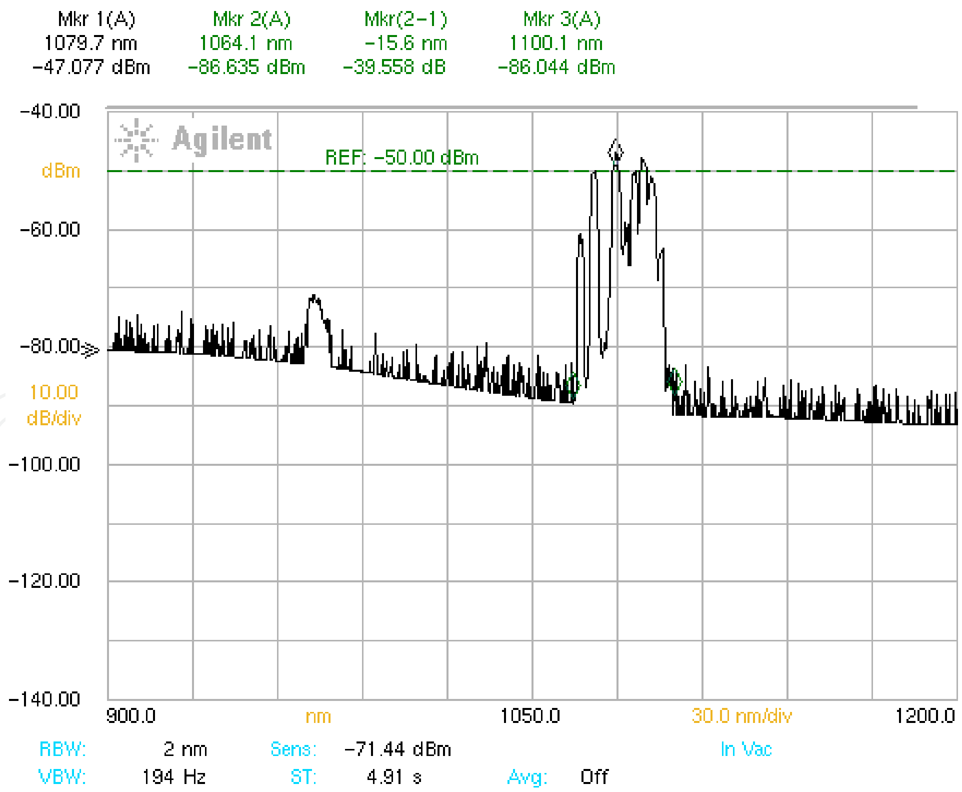


Figure 6. Output spectrum of Yb-doped CW fiber laser at the maximum output power of 165 W.

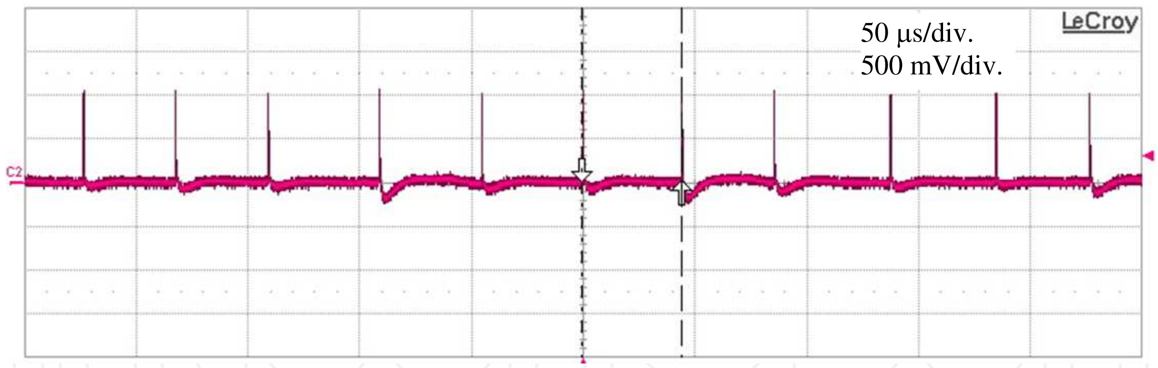


Figure 7. Self-pulses in the laser output with resonator mirrors slightly misaligned.

5. Self-pulsing dynamics of all-fiber oscillator configuration using FBG mirrors

Figure 8 shows a schematic view of 115 W of all-fiber Yb-doped CW fiber laser. In this all-fiber laser configuration, a Yb-doped double-clad fiber has been used as the gain medium having a core diameter of 20 μm and an inner-clad diameter of 400 μm. NAs of the core and inner clad are 0.075 and 0.46, respectively. Inner clad has an octagonal shape to avoid excitation of skew modes.

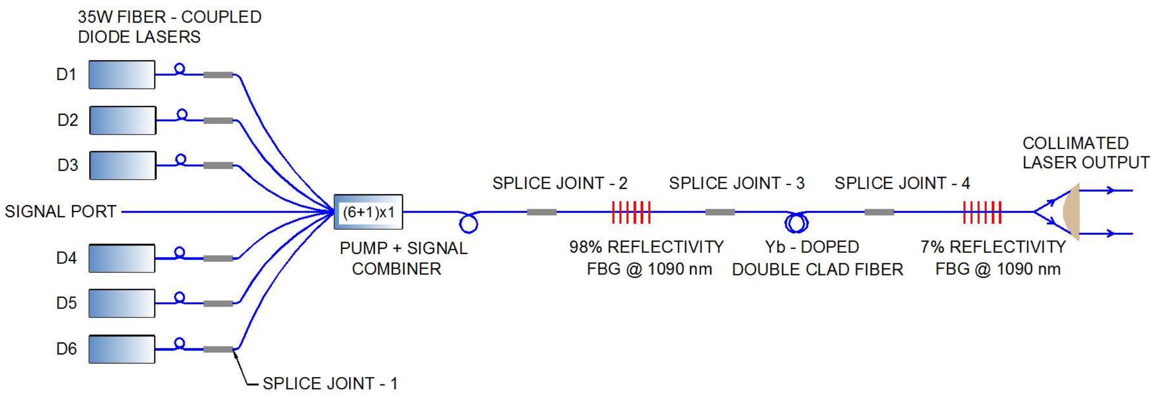


Figure 8. A schematic view of 115 W of all-fiber Yb-doped CW fiber laser.

Inner-clad pump absorption of the Yb-doped fiber at 975 nm is 1.7 dB/m. For efficient absorption of the pump beam, 10 m length of the active fiber has been used, which provides total pump absorption of ~17 dB. For pumping of Yb-doped fiber, a diode pump module of six fiber coupled diodes has been made. Each fiber coupled diode provides an output power of 35 W at 975 nm at 20 °C case temperature. Fiber coupled diode contains an optical fiber with a core diameter of 200 μm and an NA of 0.22. This diode-pump module has been spliced to (6+1)×1 fiber-optic signal and pump combiner. The core diameter of the fiber-optic pump combiner at

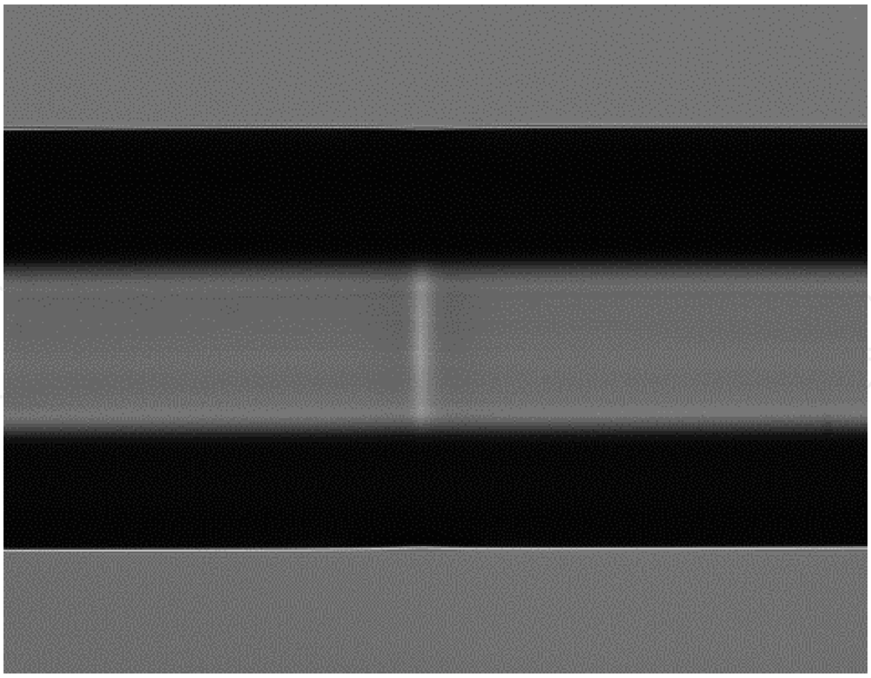


Figure 9. Optimized splice joint of 400 μm inner-clad diameter double-clad fiber with compatible fiber Bragg grating in double-clad fiber.

the output end is 400 μm with an NA of 0.46. Further, the output end of the fiber-optic pump combiner has been spliced to a FBG of ~98% reflectivity. This FBG is written in a compatible double-clad fiber, and it has a peak reflectivity at 1090 nm with a bandwidth of 0.2 nm. One end of Yb-doped fiber has been spliced to the other end of this HR FBG. Another FBG of ~7% reflectivity at 1090 nm has been spliced at the other end of Yb-doped fiber to make an all-fiber fiber laser oscillator. This 7% reflectivity FBG has also been written in a compatible double-clad fiber with a peak at 1090 nm and a bandwidth of 1.5 nm. The diode-pump module of six fiber-coupled diodes, pump combiner package, and FBGs are being cooled by means of water-cooled heat sinks and a closed loop water cooling unit at 20 °C of water temperature. A power supply unit has been used to control and operate all the six fiber-coupled laser diodes in series. The power supply unit provides voltage variations in the range of 0–15 V and current variations in the range of 0–100 Amp. Optimization of splice joint-1 of diode pump module with (6+1)×1 fiber-optic signal and pump combiner having 200 μm core diameter silica–silica fibers resulted in a transmission efficiency of 97%. After splice joint-1, the transmitted pump power from the pump combiner was 204 W at the maximum combined diode input pump power of 210 W. After splice joint-2 of the fiber-optic pump combiner with HR FBG mirror, transmission efficiency of 94% was achieved and the transmitted pump power from FBG was 192 W. Figure 9 shows optimized splice joint of 400 μm inner-clad diameter double-clad fiber with compatible FBG in double-clad fiber.[38]

Figure 10 shows variation of laser output power as a function of input pump power. It can be seen that there is no rollover even at the maximum output power due to thermal effects in Yb-doped double-clad fiber or any other fiber component. Threshold for lasing was about 17.0 W. An optical-to-optical conversion efficiency of 55% and a slope efficiency of 57% have been

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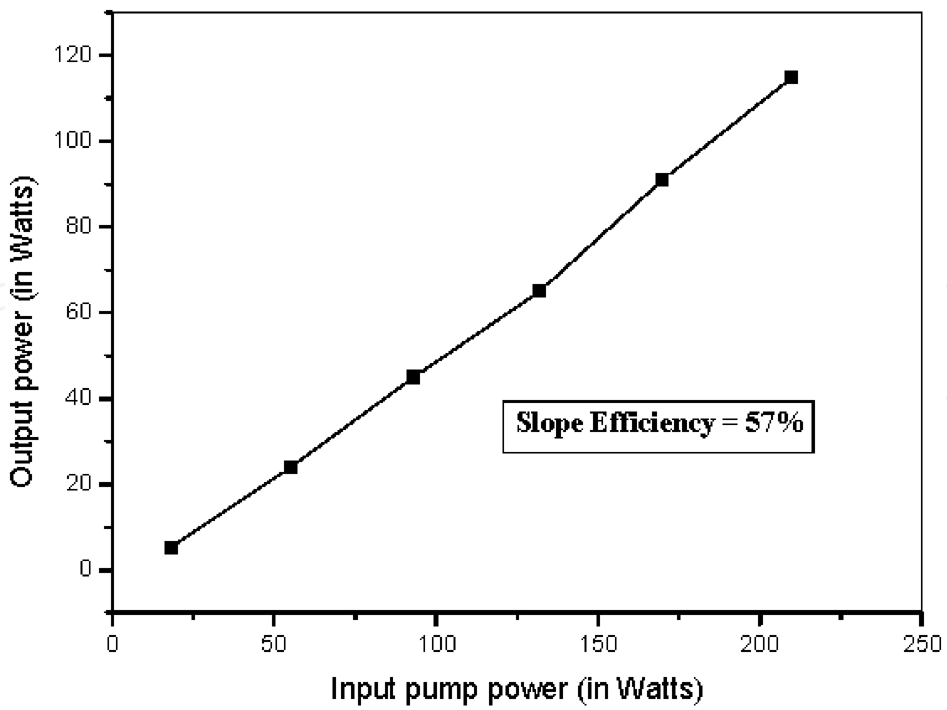


Figure 10. Variation of output laser power vs input pump power.

achieved in this all-fiber Yb-doped fiber laser oscillator configuration. Figure 11 shows wavelength spectrum of output laser signal at the maximum output power of 115 W. It shows signal peak at 1089.7 nm having a 3 dB linewidth of 0.64 nm. Major problems faced in this development were self-pulsing, optimization of splice joints, and heat removal. Self-pulsing was removed by minimization of intracavity losses and heat load from Yb-doped fiber was removed by tightly winding it on a copper spool, so that heat from fiber is conducted through copper spool. Intracavity loss is basically introduced by splice joints of FBGs with Yb-doped fiber. The splice joint loss was minimized by varying splice parameters such as fusion power, rate of fusion, argon flow rate, etc., using a commercial fusion splicing work station. This work station shows an estimated loss using image of splice joints. Although, it does not show an accurate data for splice loss, but a lower value of estimated loss indicates a better splice joint. Using this data, several splices were carried out by varying splice parameters and these joints were tested in resonator by measuring lasing threshold. A lower value of threshold was achieved with minimized estimated splice joint loss. During the testing of splice joints, it was found that laser output contained self-pulses and it became difficult to increase output power due to damage of FBG and fiber-end facets. It was found that with minimum value of lasing threshold and estimated loss, the self-pulses were removed and a truly CW output was observed without self-pulsing and no damage of fiber components took place. Figure 12(a) shows oscilloscope trace of self-pulsing amplitude with higher splice loss, and Figure 12 (b) shows oscilloscope trace with minimized splice loss. These traces were recorded using a 1 GHz photoreceiver and 1 GHz oscilloscope. It shows that self-pulse amplitude is minimized with reduction in intracavity splice losses. Laser output was emitted through the 20 μm core of doped fiber with a full-angle divergence of 150 mrad. V-number of the fiber is 4.425, and it can support about eight transverse modes. However, it was made to operate in single-transverse mode by winding it on a spool of 150 mm diameter, so that higher order modes are leaked out by bend induced loss. A laser cutting nozzle was made, which contains a 20 mm focal length lens for collimation and another 40 mm focal length lens for focusing to have a focused spot diameter of 40 μm. Using this cutting nozzle and oxygen as assist gas, micro-cutting of up to 2.5 mm thick stainless steel sheets and tubes was carried out with a kerf width of less than 200 μm.

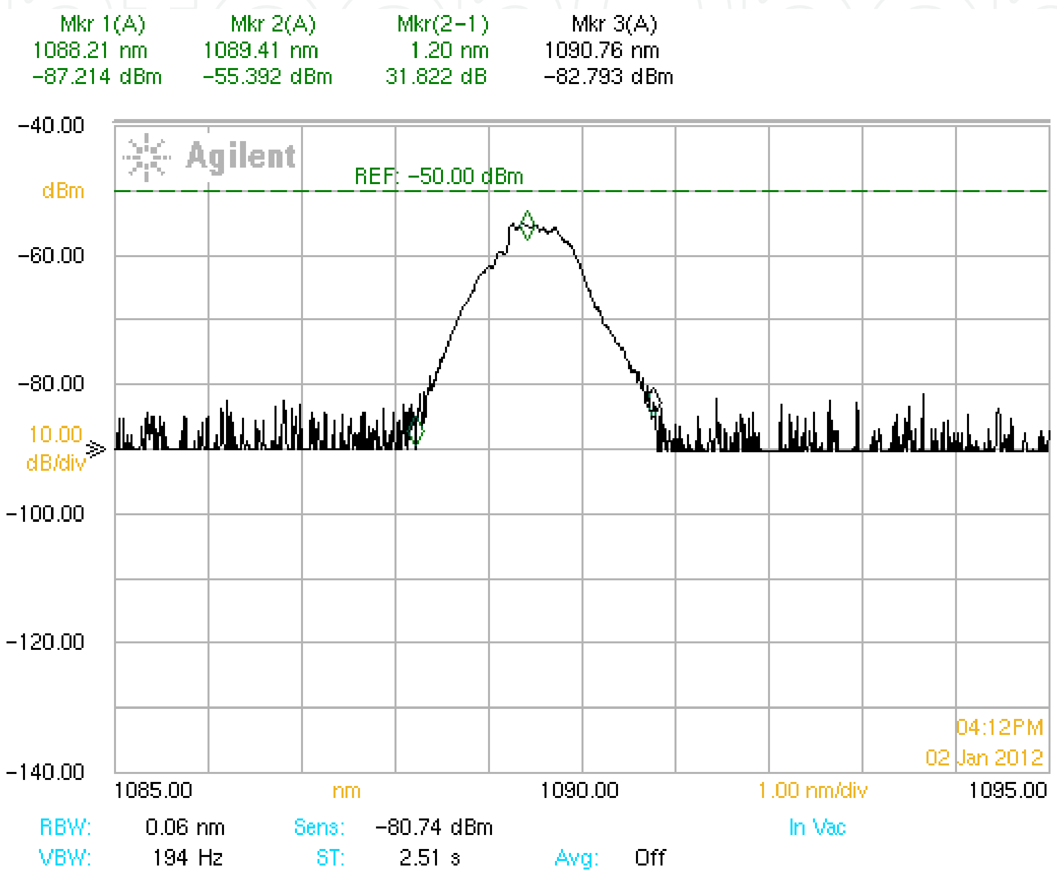


Figure 11. Wavelength spectrum of output laser signal.

6. Generation of 215 W of CW output power using all-fiber MOPA configuration and its self-pulsing dynamics

Figure 13 shows schematic of experimental setup of high-power 215 W of all-fiber Yb-doped CW fiber laser using MOPA configuration. In this all-fiber laser configuration, all-fiber oscillator as described in earlier in this chapter has been utilized. The output of oscillator was amplified by using another (6+1)×1 fiber-optic pump and signal combiner. From the oscillator stage, 115 W of output was achieved, which was further amplified to an output power of 215 W at the amplifier stage. As the laser is emitted from a very small (20 μm) core diameter of Yb-doped fiber, it is prone to damage by dust particles. Thus, at the exit end of amplifier, an end

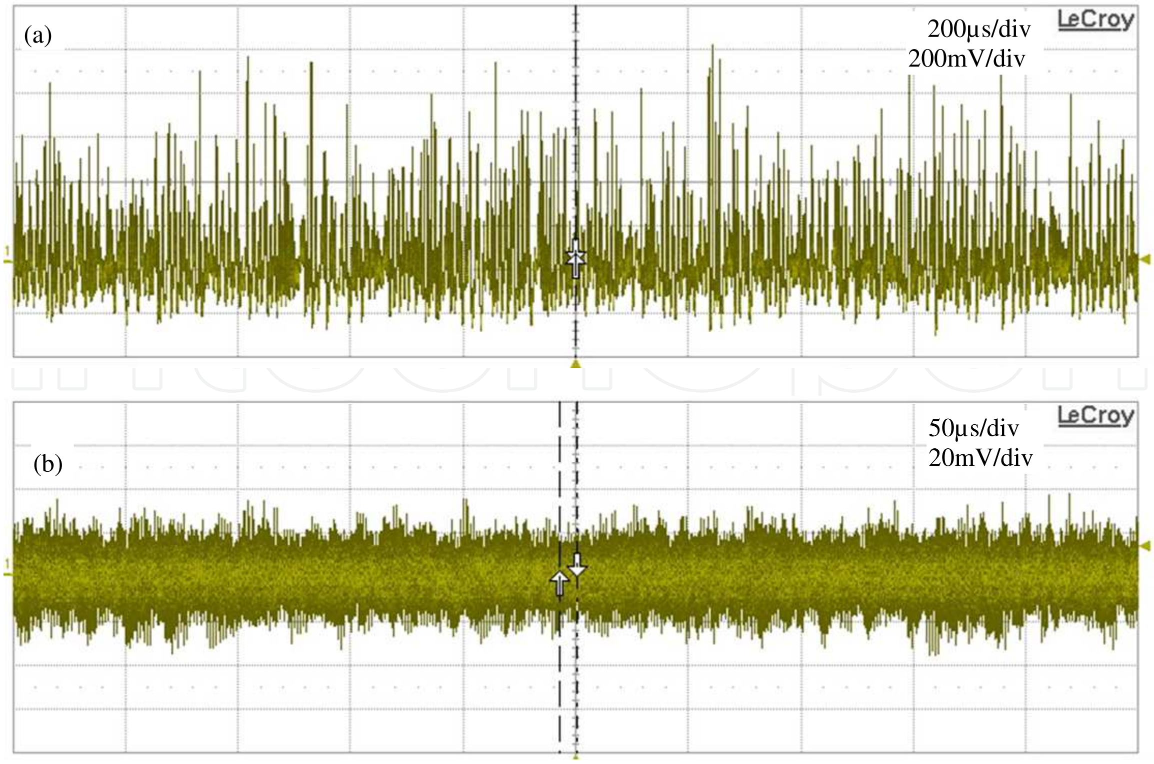


Figure 12. (a) Oscilloscope trace of self-pulses with higher splice loss, and (b) oscilloscope trace of laser output with minimized splice loss.

cap of 400 μm diameter was spliced to sustain higher damage thresholds. An optical-to-optical conversion efficiency of 55% and a slope efficiency of 57% have been achieved in this all-fiber Yb-doped fiber laser MOPA configuration. Output signal was peaked at 1089.7 nm having a 3 dB linewidth of 0.64 nm.[39]

As described in previous sections, major problems faced in this development were self-pulsing, optimization of splice joints, and heat removal. Self-pulsing, which is generation of high peak power ns-pulses even with CW pumping, results in catastrophic damage of fiber components and diode laser. It was removed by minimization of intracavity losses by minimization of losses through splice joints in the cavity. The splice joint loss was minimized by varying splice parameters such as fusion power, hot push, rate of fusion, argon flow rate, etc., using a fusion splicing work station. Heat load from Yb-doped fiber was efficiently removed by tightly winding it on a copper spool, so that heat from fiber is conducted through copper spool. Intracavity loss is basically introduced by splice joints of FBGs with Yb-doped fiber. Splice joints were also re-coated using low-index and high-index polymers for its protection. Figure 14 (a) and (b) shows the 2D and 3D beam profiles at the output of amplifier stage recorded using a Spiricon beam profiler, which shows that output is nearly diffraction limited with smooth variation in intensity. In this case also, if the slice joint losses are not minimized, it may result in higher intracavity losses, and consequently, result in high peak power self-pulses in the laser output. If not checked, these self-pulses may contain sufficient peak power to damage in-line fiber components and diode laser also.

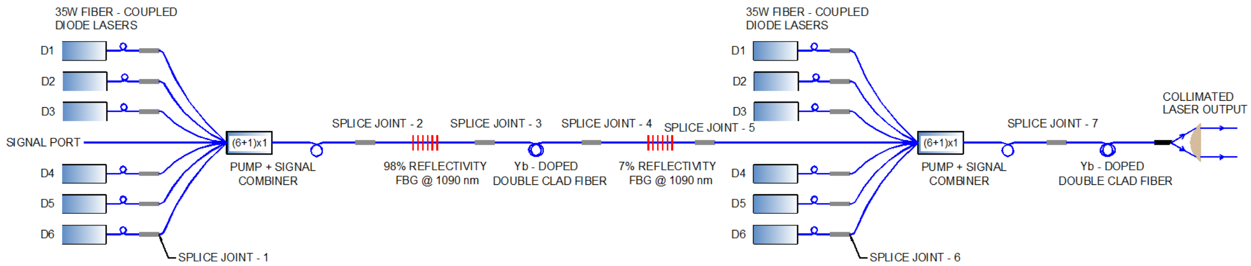
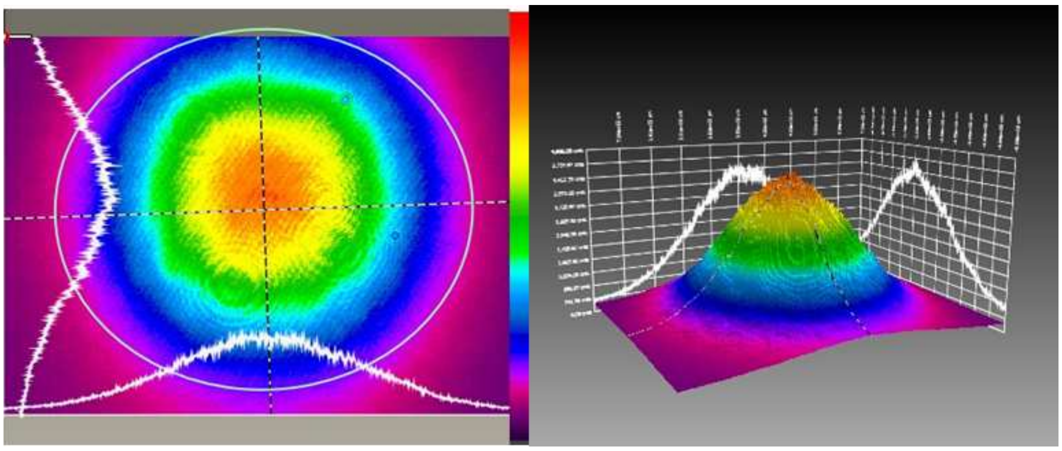


Figure 13. Schematic of experimental set up for MOPA configuration.



(a) (b)

Figure 14. (a) 2D and (b) 3D beam profile recorded at the output of 215 W of Yb-doped CW fiber laser.

Thus, most of the fiber laser configurations suffer from self-pulsing. It is necessary to suppress self-pulsing in the output by a careful choice of doped fiber length, resonator configuration, and output spectrum with minimization of intracavity losses before proceeding towards high-power CW output from Yb-doped fiber lasers.

7. Conclusion

In conclusion, study on high-power Yb-doped CW fiber laser shows that higher intracavity losses lead to generation of unwanted high-peak power self-pulses in laser output which may damage fiber components and inhibit high-power laser generation. Hence, in order to achieve high-power CW fiber laser output, it is necessary to carefully select doped fiber length, resonator configuration, and reduce intracavity losses by minimizing losses at splice joints in the cavity and also to effectively manage heat load of active fiber and all-fiber components.

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