International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I6P216
Volume 70 Issue 6, 129-136, June 2022

Original Article

Performance Optimization of Erbium-Ytterbium Doped Fiber for Single Stage High Power Amplifier

Binu R[1], Vallikannu R[2]

[1,2]*Electronics and Communication Engineering, Hindustan Institute of Science and Technology, Tamil Nadu, India.*

[1]binujiju@gmail.com

Received: 09 April 2022 Revised: 26 May 2022 Accepted: 11 June 2022 Published: 27 June 2022

Abstract – *Erbium Ytterbium Co-doped Fiber Amplifiers ensure optical signal amplification in fiber optic transmission systems considering the aspect of cost and energy efficiencies. Co-doping with ytterbium is more significant because of the high gain and pump efficiency achieved using high-power pump lasers coupled to the double-cladded structure of the Erbium-Ytterbium fiber. The performance of a high-power Amplifier designed with Erbium ytterbium co-doped fiber, which is pumped by a 940 nm pump laser, is analyzed and validated experimentally. The amplifier gives an output power of 3 W in the wavelength region from 1520 to 1570 nm using a single-stage design and provides an efficient, low noise amplification for long-haul optical communication networks. The performance factors of such an amplifier are detailed, and the specifications are optimized through experimental validations.*

Keywords *- Amplified Spontaneous Emission, Dual Clad Fiber, Erbium-Ytterbium Doped Fiber, Pump Absorption, Noise Figure*.

1. Introduction

Widespread acceptance of Fiber-To-The-Home (FTTH) services has created a huge demand for High Power Optical Amplifiers. Optical amplification based on cladding pump technology helps achieve higher output power in the range of 3-5 W and is ideal for FTTH and optical Cable Television (CATV) applications. From a capital and operational expenditure perspective, the cladding-pumped high power simplifier scheme gives one of the most suitable amplification approaches for realizing the high optical output.

In FTTH networks, an optical signal is delivered to multiple users from a single head end. EDFAs are used to amplify the signals to distribute among many users. High-power amplifiers can be used to replace multiple EDFAs. For example, a scheme that needs 4 to 8 sets of 4-port 16 dBm amplifiers can be replaced with a single high-power amplifier (16 dBm per port with 26 ports) and overcome the higher splitting loss.[1] It helps reduce the system's overall cost, reduces the space requirement on the rack, saves electrical power consumption, *etc*. Apart from this, high-power amplifiers find applications in material processing, sensing, and LIDAR as optical sources when they amplify pulsed input signals. High-power amplifiers are a good candidate for laser sources of the next-generation Gravitational Wave Detectors
(GWD).[2]

The most critical part of the fiber amplifier is the active fiber which can be either Erbium-doped or Erbium Ytterbium-doped, where the actual optical amplification occurs. In applications requiring tens of watts of power, ytterbium-doped fiber is limited by the low absorption at pump wavelengths. Co-doping with ytterbium will enhance the amplification and benefits in the wide selection of pump wavelengths. [3,4,5] In such cases, the best Erbium Ytterbium-doped fiber will have ultra-high efficiencies and a low amplification threshold to extract the maximum gain for a fixed pump power.

Erbium Ytterbium Doped Fiber Amplifier (EYDFA), having 0.19W output power, is demonstrated using a single-stage scheme.[6] EYDFA uses a dual-stage configuration in which the first stage is Erbium-doped fiber pumped at 980 nm and the second stage is Erbium-Ytterbium doped fiber pumped at 1064 nm, giving an output of 0.39W.[7] Multi-stages will increase the system's complexity for a commercial amplifier design because of the different pump lasers used for energizing the doped fiber. The pump lasers are to be driven using different driver circuits, which will add to the device's total cost. EYDFA configuration having 34dB signal gain is also demonstrated with an optimized length of the Erbium Ytterbium-doped fiber.[8] No discussion was given on the noise characteristics and Amplified Spontaneous Emission (ASE) measurements of such a configuration. This paper discusses the approach for a 3 W EYDFA with a single-stage configuration. The performance factors of the EYDFA are optimized for getting the high output power of 3 W.

2. Amplification using Erbium-Ytterbium Doped Fiber

The active fiber used is a dual-clad, cladding-pumped Erbium-Ytterbium fiber. As the name specifies, it has two claddings in addition to the core. Figure 1 shows the structure of a dual-clad fiber. The core carries the signal to be amplified while the first cladding confines the multimode pump laser. It has many advantages over the traditional core pumped erbium fiber. [9] The first cladding provides a multimode path for the pump laser, thus allowing the use of higher-power multimode pump lasers. [10]

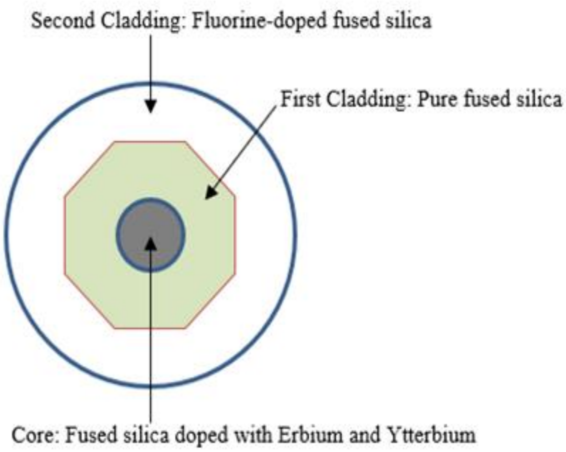

Fig. 1 Illustration of a dual clad fiber with octagonal inner cladding

Inside the Er-Yb fiber, the pump signal at ≈ 915 or 940 nm will excite the ytterbium ions to their excited state. These exciting ions will then transfer the energy to the erbium ions. The efficiency of transfer of energy from ytterbium to erbium is higher than exciting erbium ions directly. Once erbium is excited, it will de-excite to the ground state, releasing a photon of a similar wavelength as one that strikes it, i.e., stimulated emission. [11]

As Er-Yb fiber is excited with pump light, a population inversion occurs in the Yb energy levels. Once population inversion is achieved, energy is transferred from the excited levels of Yb to exciting levels of Er. If this energy transfer is inefficient enough, then energy decay will occur within the Yb energy levels resulting in parasitic emissions centered at the 1000 nm wavelength range. [12] Figure 2 shows a typical Er-Yb emission spectrum with 940 nm pumping, where the green line shows the amplified optical output. [12]

Above a certain pump power value, there exists parasitic ASE, which is shown as the red line in Figure 2. If the Er-Yb fiber does not have an optimized design, then the parasitic ASE will become self-lasing at higher pump powers, as shown in a red dotted line in Figure 2. This self-lasing affects the signal amplification, which will result in a drop in the output power. The green dotted line indicates the power drop in amplified output.

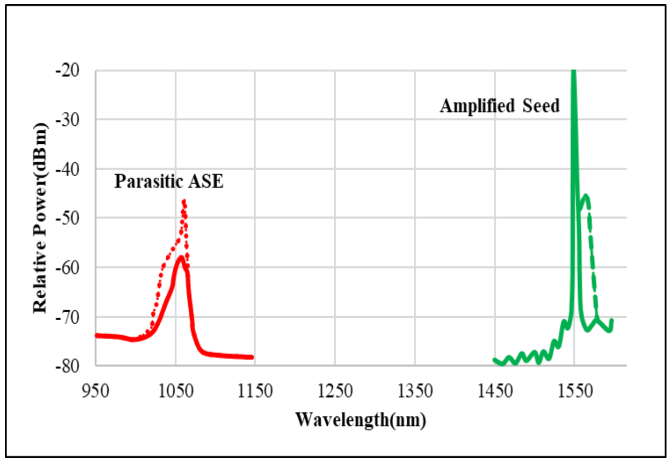

Fig. 2 Emission Spectrum of Er-Yb Co-doped Fiber

Therefore, efficiency, threshold, parasitic emission, and factors such as fiber length, absorption, etc., must be monitored to characterize the amplifier system.

2.1. Performance factors for Er-Yb Fiber Amplifier

Several performance factors must be considered to optimize the high-power amplifier system. The critical parameters are listed below.

- Er-Yb Fiber length
- Pump absorption
- Pump wavelength
- Pump Power
- Input signal Power

These factors have a direct impact on the performance of the EDFA and require careful consideration.

Er-Yb Fiber length is a very important parameter that directly contributes to the amplifier's efficiency. Manufacturers typically specify pump absorption of the fiber in dB per meter. Thus longer fibers can achieve better absorption. However, as the fiber length increases beyond a certain range, the signal in the 1550nm wavelength will be re-absorbed by the active elements to excite from the ground state to the excited state. It will considerably weaken the signal, and hence the amplification will deteriorate.

Figure 3 shows the simulation results showing the dependency of fiber length on signal power for pump power values at 5 W and 10 W.

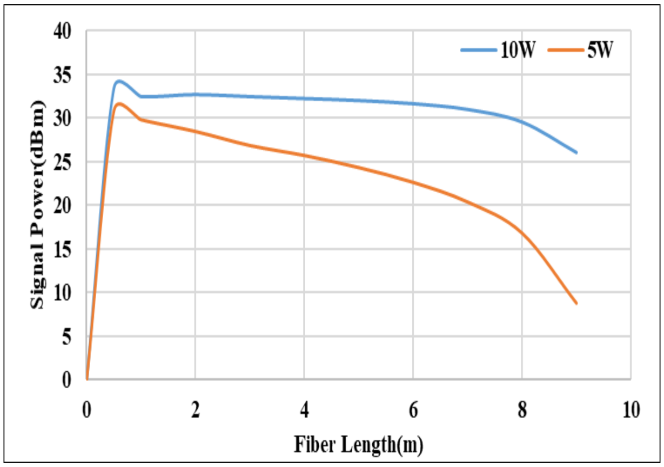

Fig. 3 Simulation result for the fiber length optimization with Opti System tool

A set of baseline parameters exists for simulating the amplifier using Erbium Ytterbium-doped fiber.[13] Table 1 gives the values of the fiber parameters the Fiber manufacturer gave, which were used in the simulation. There is parasitic emission at 1000 nm for small fiber lengths, which will add to the total output power. Simulation results show that an optimum performance with a stable output power is possible using a fiber length of 4-6 m.

Table 1. Simulation parameters of Erbium-Ytterbium doped fiber

Parameter	Value	Unit
Core radius	5	μm
Doping Radius	5	μm
Numerical aperture	0.2	-
Er ion density	5.14×10^{25}	m^{-3}
Yb ion density	6.2×10^{26}	m^{-3}
Er metastable lifetime	10	ms
Yb metastable lifetime	1.5	ms
Signal loss	1.5	dB/m
Pump loss	1.0	dB/m

Pump Wavelength is yet another critical factor. Because absorption of the pump signal at different wavelengths varies for the active fiber, this will also affect the emission characteristics. The selection of pump laser is significant in optimizing the gain of the amplifier.

Selecting the optimum Pump Power is also critical. Pump power is directly responsible for signal amplification. The more the pump power, the more will be the amplification. However, after a certain maximum pump power, there will be a lot of active ions in the excited state, and they go into saturation. In this condition, instead of stimulated emission, the excited ions will start to decay to the ground state randomly, i.e., spontaneous emission will occur. This emission happens around the 1000 nm wavelength range and will cause more exciting ions to decay to the ground state. This emission at the 1000 nm wavelength range will also be present along with the amplified signal and at the output of the optical amplifier. Hence it is necessary to limit the pump power to a reasonable level for proper amplification.

Finally, the Level of the input signal (to be amplified) plays a role in the efficiency and performance of the amplifier. By theory, any signal can be amplified by the doped fiber, but there are practical upper and lower limits to the input that can be given. The amplifier's efficiency will be low for too low input values, so the pump power has to be increased to get the required amplification from it. If the signal level is too high, it will lead to gain saturation and signal distortion. To achieve low-noise performance in CATV systems, the amplifier input power is typically greater than 3dBm. [15]

2.2. Fiber Comparison

Considering the critical factors for amplification, Er-Yb fibers from different manufacturers were compared for their specifications. The technical comparison is given in Table 2.

Table 2. Comparison of specifications of Er/Yb fibers from different manufacturers

Parameters	Fiber 1	Fiber 2	Fiber 3	Fiber 4
Operating wavelength(nm)	1530-1625	1520-1570	1520-1570	1520-1570
Core NA	0.21	0.19±0.02	0.21	0.17
First Cladding NA	≥0.46	0.46	0.45	0.45
Cladding absorption at 915nm (dB/m)	1.0±0.25	2.9-3.6	1.93	1.5
Core absorption near 1530nm(dB/m)	40±10	55-75	76	20.0
Core Diameter(μm)	5.5	12±7	10.1	10.0
Cladding diameter(μm)	125±2.0	125±3	125	125
Cladding shape(μm)	Hexagonal	Octagonal	Hexagonal	Hexagonal
Coating diameter(μm)	245±15	245±15	239	245±15

3. Experimental Method

The basic architecture of a high-power amplifier with Er/Yb co-doped fiber is shown in Figure 4.

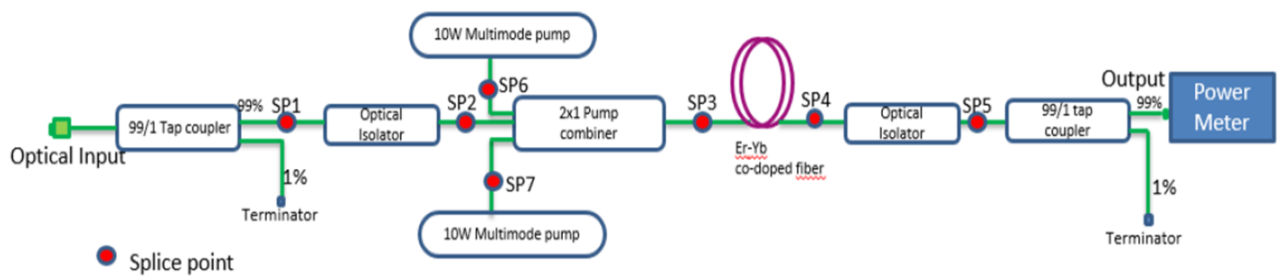

Fig. 4 Architecture of a high power amplifier with Er-Yb Co-doped Fiber

The experimental setup consists of a light source at 1550nm at power levels below 100mW as the input. It can either be a commercially available laser module or an optical signal from an existing fiber optical network. This input light is amplified in a single stage. Pump sources at 940nm are coupled to the co-doped fiber using a pump combiner. Optical isolators with an insertion loss of 0.5dB are used to block all unwanted signals from propagating to the input. Suitable optical couplers with minimum loss are used to tap a small amount of input and output power to monitor the amplifier performance. Output is measured using a power meter, and spectrum is analyzed using an optical spectrum analyzer.

Depending on the system architecture and the targeted output power and efficiencies, the choice of the Er-Yb fiber is critical to deriving the maximum gain for a fixed pump power. Fibers mentioned in Section 2.2 are used for trials.

4. Results and Discussion

Initial tests were done using 10 m of each fiber, cut down by 0.5 m. Output power is continuously monitored using an optical power meter.

For Fiber 1, the highest output power is achieved at a fiber length of 7.5 m for an input power of 4 dBm. For Fiber 2, the highest power is achieved at a fiber length of 7.5 m for an input power of -3 dBm. For Fiber 3, fiber length is optimized to 6.5 m, and the highest output power is achieved at an input of -2 dBm. For Fiber 4, the optimum fiber length is 10 m for an input power of 6 dBm.

Table 3. Amplified Output Power obtained from Fiber 1

Pump Current(mA)	Pump Power (W)	Output Power (W)
1000	3.18	0.57
2000	4.7	0.93
3000	6.12	1.24
4000	7.73	1.59
5000	9.19	1.94
6000	10.8	2.29
7000	12.33	2.55
8000	13.98	2.83

Table 4. Amplified Output Power obtained from Fiber 2

Pump Current(mA)	Pump Power (W)	Output Power (W)
1000	3.18	0.11
2000	4.7	0.35
3000	6.12	0.61
4000	7.73	0.83
5000	9.19	1.12
6000	10.8	1.46
7000	12.33	1.8
8000	13.98	2.08

Table 5. Amplified Output Power obtained from Fiber 3

Pump Current(mA)	Pump Power (W)	Output Power (W)
1000	3.18	0.35
2000	4.7	0.69
3000	6.12	1.1
4000	7.73	1.49
5000	9.19	1.92
6000	10.8	2.34
7000	12.33	2.77
8000	13.98	3.16

Figure 5 shows the output power obtained at different pump power values for Fiber 1, and the data are tabulated in Table 3. Input power given is 4 dBm, and the high power achieved is 2.83 W at 13.98 W pump power. Inset shows the optical spectrum of the amplified signal in the wavelength range of 1525 to 1570 nm. The red dotted circle shows the high ASE near 1530 nm, which is nearly -34 dBm which will translate to the high noise figure of the amplifier.

Table 6. Amplified Output Power obtained from Fiber 4

Pump Current(mA)	Pump Power (W)	Output Power (W)
1000	3.18	0.15
2000	4.7	0.24
3000	6.12	0.34
4000	7.73	0.45
5000	9.19	0.57
6000	10.8	0.7
7000	12.33	0.82
8000	13.98	0.93

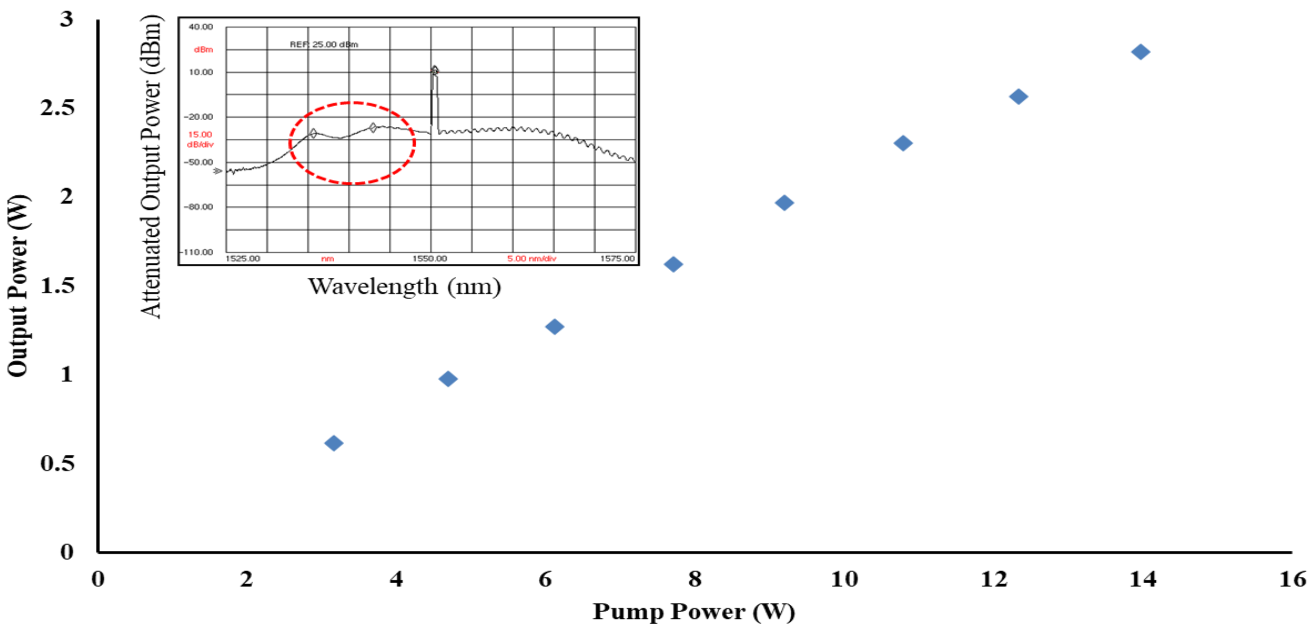

Fig. 5 Output power of the amplified signal for different pump power values obtained from Fiber 1

Figure 6 shows the output power obtained at different pump power values for Fiber 2, and the data are tabulated in Table 4. Input power given is 4 dBm, and the high power achieved is 2.08 W at 13.98 W pump power. Inset shows the optical spectrum of the amplified signal in the wavelength range of 1525 to 1570 nm. The spectrum shows a low noise compared to Fiber 1, and the measured ASE is -44 dBm.

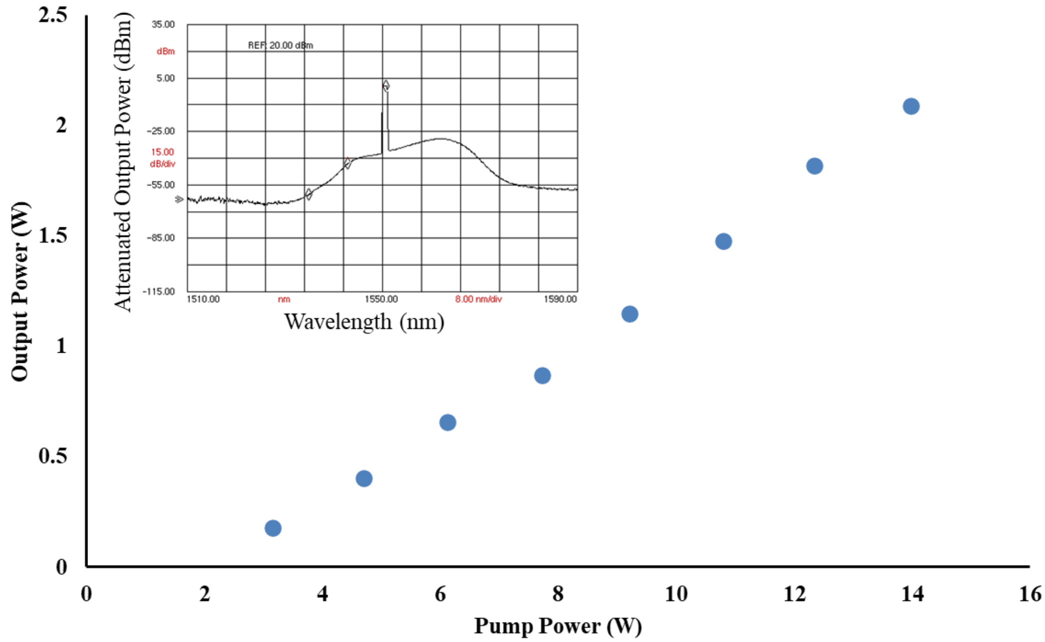

Fig. 6 Output power of the amplified signal for different pump power values obtained from Fiber 2

Figure 7 shows the output power obtained at different pump power values for Fiber 3. The highest output power achieved is 3.16 W at 13.98 W pump power at 4 dBm input. Table 5 gives the Output Power values for different pump powers. The optical spectrum shows a low noise compared to Fiber 1 and 2, and the measured ASE is -52 dBm.

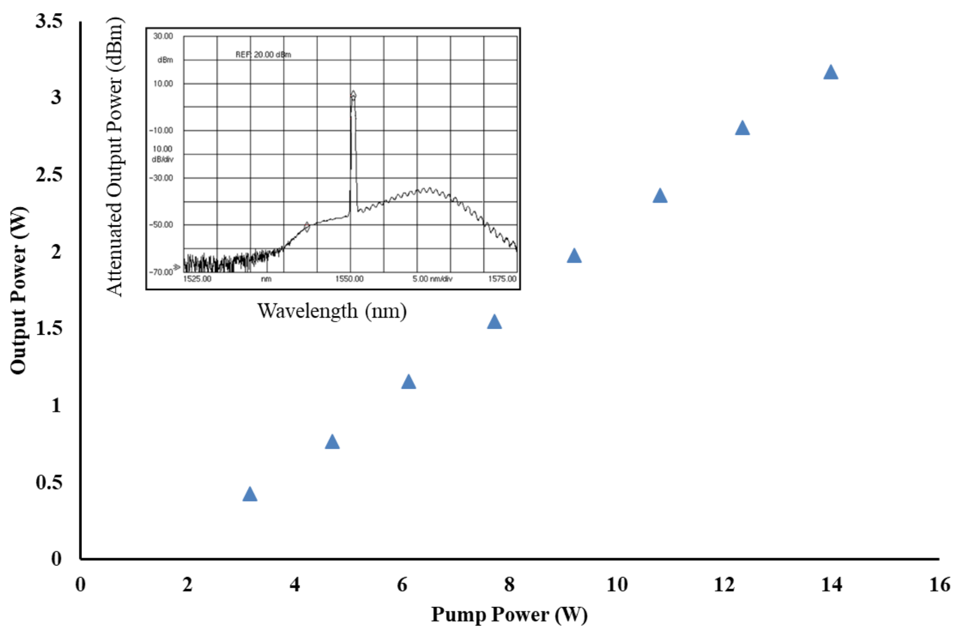

Fig. 7 Output power of the amplified signal for different pump power values obtained from Fiber 3

Figure 8 shows the output power obtained at different pump power values for Fiber 4. The high output power of 0.93 W is obtained at 13.98 W pump power. Table 6 gives the output Power values achieved for different pump powers. The optical spectrum shows a high noise compared to Fiber 2 and 3. The measured ASE is -43dBm.

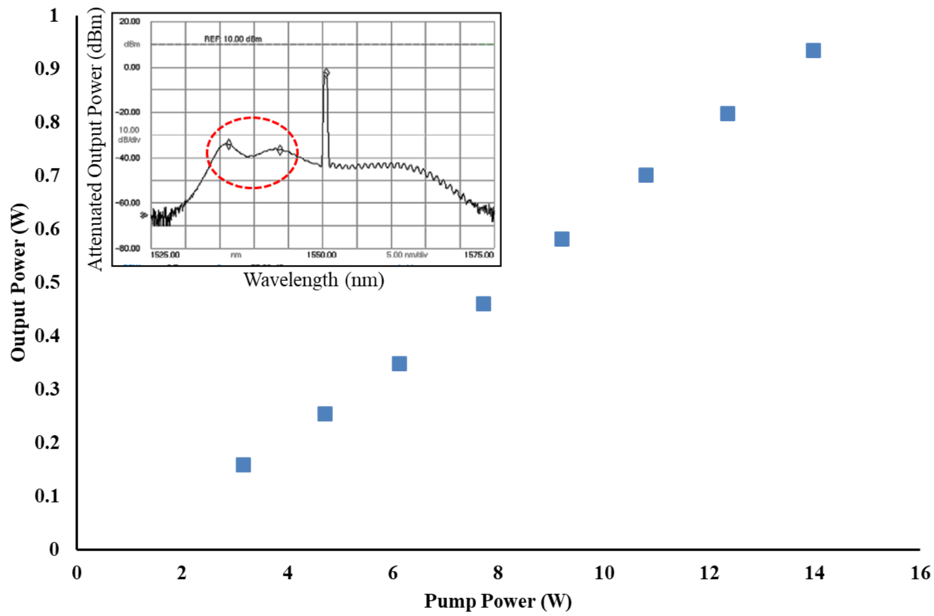

Fig. 8 Output power of the amplified signal for different pump power values obtained from Fiber 4

From the trials, the fiber length is optimized to 6-7 m for an Er-Yb doped fiber with a Core absorption of 55-76 dB/m at 1530nm. A core diameter of 10-12 µm gives an efficient coupling of the pump signal for exciting the rare-earth ions. The pump power used is 14 W at 940 nm for amplifying the input signal in the wavelength range of 1525nm to 1570nm so that the measured parasitic ASE at 1000nm is found to be minimum.

5. Conclusion

The performance of a high-power EYDFA of 3W output is experimentally demonstrated, and the performance factors are optimized. The trials help estimate the optimum length of Erbium Ytterbium co-doped fiber and its other specifications to achieve a high gain with low noise. The high-power output requirement of 3W is possible with a single-stage EYDF design. The supported input optical power range is -2 to +10 dBm. The risks identified are significant heating and optical leakage observed at the dissimilar splice points, which point out better splice optimization and thermal management at key splice points.

Acknowledgments

This work is completed with the support of SFO Technologies Pvt Ltd, Kochi. The authors express their sincere gratitude to the managing director and Chairman of SFO Technologies Pvt Ltd, Kochi.

References

[1] Mirek Karasek, Optimum Design of Er^{3+}-Yb^{3+} Co-Doped Fibers for Large Signal High-Pump-Power Applications, IEEE J. Quantum Electron. 33(10) (1977) 1699-1705.

[2] M. Steinke, J.Neumann, D.Kracht and P.Wessels, Gain Dynamics in Er^{3+}:Yb^{3+} Co-Doped Fiber Amplifiers, Optics Express. 23(11) (2015) 14946-14959.

[3] J. Nilsson, P.Scheer and B.Jaskorzynska, Modeling and Optimization of Short Yb^{3+}-Sensitized Er^{3+}-Doped Fiber Amplifiers, IEEE Photonics Tech. Lett. 6 (3) (1994) 383-385.

[4] Supe.A, Olonkins.S, Udalcovs.A, Senkans.U, Murnieks.R, Gegere.L, Prigunovs.D, Grube.J, Elsts.E, Spolitis.S, Cladding-Pumped Erbium/Ytterbium Co-doped Fiber Amplifier for C-Band Operation in Optical Networks, Appl. Sci. 11 (2021) 1702.

[5] Eldad Yahel, Amos Hardy, Efficiency Optimization of High-Power, Er^{3+}-Yb^{3+-} Codoped Fiber Amplifiers for Wavelength-Division-Multiplexing Applications, Opt.Soc.Am.B. 20(6) (2003) 1189-1197.

[6] S.W.Harun, M.R.A.Moghaddam and H.Ahmad, High Output Power Erbium-Ytterbium Doped cladding pumped Fiber Amplifier, Laser Physics. 20 (10) (2010) 1899-1901.

[7] Paul F.Wysocki, Namkyoo Park and David DiGiovanni, Dual-Stage Erbium-Doped, Erbium/Ytterbium-Codoped Fiber Amplifier with up to +26dbm Output Power and a 17-Nm Flat Spectrum, Optics Letters. 21(21) (1996) 1744-1746.

[8] M.R.A.Moghaddam, S.W.Harun, R.Parvizi, Z.S.Salleh, H.Arof, A.Lokman, H.Ahmad, Extperimental and Heoretical Studies on Ytterbium Sensitized Erbium-Doped Fiber Amplifier, Optik-Int.J.Light Electron Opt. 122(10) (2011) 1783.

[9] Dmitri Kouznetsov, Jerome V.Moloney, Efficiency of Pump Absorption in Double-Clad Fiber Amplifiers II, Broken Circular Symmetry, J. Opt. Soc. Am. B. 19(6) (2002) 1259-1263.
[10] Rudiger Paschotta, J.Nilsson, A.C.Tropper and D.C.Hanna, Ytterbium-Doped Fiber Amplifiers, IEEE. Quantum Electron. 33(7) (1977) 1049-1056.
[11] Kuthan Yelen, Louise M.B.Hickey, Mikhail N.Zervas, Experimentally Verified Modeling of Erbium Ytterbium Co-Doped DFB Fiber Lasers, J. of Lightwave Tech. 23(3) (2005)1380-1392.
[12] Nufern Tutorial- Selecting the Optimal Er/Yb Doped Optical Fiber: Design Considerations and System Performances.
[13] George C.Valley, Modeling Cladding-Pumped Er/Yb Fiber Amplifiers, Optical Fiber Technology. **7** (2001) 21-44.
[14] DaljitSingh, Sumeksha Bhaskar, Gain Stabilization and Analysis of Various Configurations of Hybrid Optical Amplifiers, SSRG International Journal of Electrical and Electronics Engineering. 1(6) (2014) 32-33. https://doi.org/10.14445/23488379/IJEEE-V1I6P103
[15] Gordon Wilson, Jean-Marc Delavaux, Andrew stentz, Isaac Ryazansky, Robert Windeler, Mikhail Fishteym, Chris McIntosh, Low-Noise 1-Watt Er/Yb Fiber Amplifier for CATV Distribution in HFC and FTTWC Systems, Optical Fiber Communication Conference, Technical Digest Post conference Edition, Trends in Optics and Photonics. 37 (2002).