DESIGN AND PERFORMANCE ANALYSIS OF HOLMIUM-DOPED FIBER AMPLIFIER OPERATING AT 2µM BAND

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Abstract- This paper investigates the performance of holmium doped fiber amplifier (HDFA) with dense WDM system in the spectral region of 2000nm-2012nm. For the first time DWDM with Ho-doped fiber amplifier pumped at 1950nm is proposed which provides high gain. This wavelength and high gain can be utilized in remote sensing, scientific and defence applications. Gain of HDFA at different pumping powers and HDF lengths is obtained. A 51dB of maximum gain is achieved which is almost constant (flat) at 10W pump power with 11m of HDF length. The output is highly amplified, with 39dBm of output power at pump power of 10W and wavelength range of 2000-2012nm. The performance evaluation of the system is done by analysing the parameters like bit error rate (BER), quality factor, extinction ratio and eye-diagram. The observed values are minimum BER8.94E-31, high value of Q-factor 11.95dB, highest ER value is 18dB. So the HDFA is a high gain and high power amplifier.

Keywords- Holmium Doped Fiber Amplifier (HDFA), Dense Wavelength Division Multiplexing (DWDM), Gain, Bit Error Rate (BER).

I. INTRODUCTION

There is a continuous growth in the internet traffic in recent era which is bypassing the limit of their capacity(Ellis et al. 2010)[1]. New approaches are being investigated in optical fiber communication system to support this humongous magnitude of traffic. In recent times holmium doped fiber amplifiers have attracted huge attention at 2μm range(Zhang et al.2014)[2]. It is the new transmission window for optical communication to demonstrate low loss hollow core photonic band-gap fibers which offer ultra-low nonlinearity, low latency at the 2μm transmission window(Poletti et al. 2013)[3]. There are wide area of applications of 2 μm spectral region of laser amplifier like remote sensing, gas sensing, optical ranging and sensing, LIDAR, wireless communication and medicine(Jin et al. 2017)[4]. Holmium doped fiber operates at 2μm and gives an attractive gain medium for operation at longer wavelengths. Holmium doped silica has two possible pump band (i) 1150nm which is utilized by diode lasers, Raman fiber lasers and long wavelength ytterbium-doped fiber lasers; and (ii) 1950nm which is utilized by the thulium-doped fiber lasers. Its pumping schemes and rapid non-radiative transitions are shown in figure 1(Simakov et al. 2015 & Hemming et al. 2014)[9,10]. The ground energy state is $^5I_8$ and first excited state is $^5I_7$. The energy levels are the combination of closely spaced sub-levels. The pump light is injected at higher energy state via ground state absorption and excited state absorption phenomenon occurs. A population inversion occurs while a system exist in a state in which more photons are in excited state than un-excited energy states. If photon of particular frequency passes to the group of atoms, there is a possibility of the light being absorbed by atom which is in ground state, which will cause them to be excited to the higher energy state. If atoms are in excited state, spontaneous decay events to the ground state. The energy difference between the two states is emitted from the atom. Spontaneous emission is incoherent. If an atom is already in the excited state, it may be agitated by the passage of a photon that has a particular frequency corresponding to the energy gap of the excited state and ground state. In this case the excited atom relaxes to the ground state, and it produces a second photon of same frequency. The original photon is not absorbed by the atom, and therefore results in emission of two photon of same frequency. This process is known as stimulated emission. The two photons are coherent. It is this property that allows optical amplification(Senior)[7].

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In recent years few researchers have reported their work on HDFA. Kamynin et al. (2015) in their paper have demonstrated the maximum gain of 35.8dB for 2050nm of wavelength. Although the spectral range for the reported experiment was 2020nm to 2120nm [8]. For the first time diode pumped HDFA was demonstrated by researcher Simakov et al. (2016). He reported the peak gain of 25dB at 2040nm [5]. Resonantly pumped holmium-doped fiber amplifier was reported by Hemming et al. (2014) which is highest power amplifier, it is capable of operating in an atmospheric transmission window >2.05µm [6]. Double cladding pump power is used to achieve a high output power and 50dB gain at window >2µm.

Both erbium and holmium doped fiber are high energy laser and both are safe to eye at atmospheric transmission window (Colin et al. 2017) [11]. But operating EDFA at wavelength >1600nm is difficult due to decreasing emission so alternative rare earth dopant at 2µm wavelength is investigated. Holmium doped fiber amplifier (HDFA) has many advantages as compare to other amplifier like EDFA, TDFA etc. HDFA has high efficiency as compare to EDFA. It has high gain and high power amplifier. HDFA has wide area of sensing technique but EDFA fails at sensing properties.

Figure. 1 Ho Energy Level Diagram

In this paper, we propose a 16 channel DWDM configuration which is capable of achieving high flat gain together with high output power. The basic amplifying component used is Holmium doped fiber with different pumping configuration and different fiber length. At 1950nm pump laser, the reported gain is 51dB and output power is 39dBm in the wavelength range of 2000nm-2012nm. The maximum Q-factor and minimum bit error rate is achieved at different fiber length.

II. PRINCIPLE OF OPERATION

Figure. 2 16 Channel DWDM System with Holmium Doped Fiber Amplifier

The block diagram of the proposed configuration is shown in figure 2. The proposed framework can be used for enhancing the performance measurement of holmium doped fiber amplifier. The DWDM transmitter transmits 16 channels with 0.8nm of channel spacing. The spectral range is from 2000nm to 2012nm, at this range holmium doped fiber amplifier show low non-
linearity and 0.8nm spacing give better result. The continuous wave laser source is used to launch -20dBm input power into holmium doped fiber amplifier through co-propagating pump coupler. The ideal mux is used in the proposed design to combine all 16 channels. The co-propagating pump at pumping wavelength 1950nm is used to pump holmium doped fiber amplifier. The holmium doped fiber amplifier has two pumping bands: one is 1150nm and another is 1950nm. So in this system, 1950nm pumping band is used to achieve high output power. Dual port WDM analyzer is used to analyze the gain of the amplifier at different pumping power and fiber length. WDM demultiplexer is used to split all the channels. At the end, optical receiver which is the PIN photodiode is used to convert optical signal into an electrical signal. The performance of the proposed design is analyzed by parameters like Q-factor and bit error rate. The input power in this configuration is -20dBm. The output power of the amplifier is observed by the optical power meter. Performance of the system is analyzed at different pumping power and length of fiber. The holmium absorption and emission cross-section are shown in Figure 3.[12]

(a)  

![Ho emission parameters](image)

(b)  

![Ho absorption parameters](image)

Figure 3- (a) Emission Spectrum of Holmium Doped Fiber Amplifier (b) Absorption Spectrum of Holmium Doped Fiber Amplifier

Table 1: Parameters used in this Design

| S.No. | Parameters                  | Values   |
|-------|-----------------------------|----------|
| 1.    | Starting Frequency          | 2000nm   |
| 2.    | Frequency Spacing           | 0.8nm    |
| 3.    | Input Power                 | -20dBm   |
| 4.    | Pump Wavelength             | 1950nm   |
| 5.    | Ho Doped Fiber Core Radius  | 5µm      |
6. Doping Radius 5µm
7. Ho Ion Density 15.6e^24 m^-3

IV. THEORETICAL ANALYSIS

From Fig. 1 the pump light is injected at lower wavelength via ground state absorption and this state will decay spontaneously by radiative and non-radiative processes into first excited state whereupon stimulated absorption and emission can take place. There are number of up and down conversions so carrier rate equation of the system can be modelled as (Peterka et al. 2004)[13].

\[
\frac{dN_0}{dt} = 0 = \sum_{k=1}^{N_2} [N_1(z)W_{1,0,\lambda}(z) - N_0(z)W_{0,0,\lambda} + N_0(z)W_{1,0,\lambda} - N_0(z)W_{1,1,\lambda}]P_{k,\lambda}(z) + [N_1(z)A_{10} + N_2(z)A_{10} + N_2(z)A_{21} + N_3(z)A_{31} + N_4(z)A_{41}] + N_2(z)A_{n,r1} - N_1(z)A_{n,r1} + 2N_{101}N_0(z)N_2(z) - 2N_{1012}N_1^2(z) - 2N_{3010}N_0(z)N_3(z) - 2N_{4010}N_4(z)A_{n,r4} - N_3(z)A_{n,r3} - K_{3101}N_0(z)N_3(z) + K_{1013}N_1^2(z) - N_t - N_0(z) + N_1(z) + N_2(z) + N_3(z)
\]

(1)

\[
\frac{dN_3}{dt} = 0 = \sum_{k=1}^{N_2} [-N_3(z)A_{30} - N_3(z)A_{31} - N_3(z)A_{32} + N_4(z)A_{43}] + N_4(z)A_{n,r4} - N_3(z)A_{n,r3} - K_{3101}N_0(z)N_3(z) + K_{1013}N_1^2(z) - N_t - N_0(z) + N_1(z) + N_2(z) + N_3(z)
\]

(2)

4.1 Optical Power

The propagation of the power along the fiber can be solved by slowly varying envelop approximation, the equation of the optical power is given by (Peterka et al. 2004)[13]

\[
\frac{dp_{k,\lambda}(z,t)}{dz} = u_k \Gamma_\lambda (\sum_{i,j<\lambda} W_{i,j,\lambda}N_i(z,t) - \sum_{i,j>\lambda} W_{i,j,\lambda}N_i(z,t))P_{k,\lambda}(z,t) + \Gamma_\lambda \sum_{j<i} A_{i,j,\lambda}N_i(z,t) - u_k \alpha_k P_{k,\lambda}(z,t)
\]

(5)

Where, \(N_0(z), N_1(z), N_2(z), N_3(z)\) are carrier density in energy level 0,1,2,3. \(P_{k,\lambda}(z,t)\) is the power of each mode at position \(z\), index \(k\) is direction of travel of the light, \(\lambda\) is wavelength of mode. \(W_{i,j,\lambda}\) is stimulated transition rate, \(A_{i,j,\lambda}\) is spontaneous radiative recombination rate. \(\Gamma_\lambda\) is optical confinement factor and \(\alpha_k\) is the background loss.

4.2 Gain

Gain for each mode at the entering and existing fiber is given as (Giles et al. 1991)[14].

\[
g_{+\lambda} = \frac{P_{+\lambda}(L)}{P_{+\lambda}(0)} \quad \text{and} \quad g_{-\lambda} = \frac{P_{-\lambda}(0)}{P_{-\lambda}(L)}
\]

(6)

We are interested in the gain of the signal and pump not power so we use square root. Average power of each mode of \(E_{1,\lambda}(t)\) for \(P_{+\lambda}(0)\) and \(E_{2,\lambda}(t)\) for \(P_{-\lambda}(L)\) where \(L\) is the length of the fiber. \(E_{1,\lambda}(t)\) and \(E_{2,\lambda}(t)\) be the \(\lambda\) modes of input field.

V. RESULT AND DISCUSSION

As shown in figure 4, at the pumping wavelength of 1950nm, varying pump power and HDF length demonstrate high gain in range of wavelength is 2000nm-2012nm. At the 1W pump power and 5m HDF length the maximum gain is achieved as 24dB at 2012nm wavelength with 6dB gain window. If we change the pump power and HDF length to 5W and HDF length to 9m peak gain is obtained at 2012nm is 42dB with 10dB gain spanning. Again on varying the pump power and HDF length this time to 10W and 11m, maximum gain 51dB at 2012nm wavelength with 11 dB gain window spanning was achieved. From the Eq. 6, it is clear that gain is dependent upon the pump power so increased pump power increases the gain and the range of wavelength is 2000nm-2012nm, the saturated gain is relatively flat varying between 24dB to 51dB at all the pump powers (1W, 5W and 11W) and HDF length (5m, 9 and 11m). Here the number of photon being amplified per unit time is
much much greater than the number of photon being absorbed, and then the net result is maximum gain.

Figure. 4 Performance of the Gain vs Wavelength at 1W, 5W and 10W pump power and 5m, 9m and 11m HDF length (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)

At the pump power of 1W the output power is around 0dBm and the average power is 29.77dBm. Increasing the pump power to 5W the output increases to 15dBm on further increasing the pump power to 10W the output power reaches 20dBm. Table 2 indicates the average output power of the optical signal, therefore its values differ from the power peaks of graph in Fig. 5, 6 and 7. The power peaks in graph of Fig. 5, 6 and 7 shows the total output power. Output Spectra shown in Fig. 5, 6 and 7 proves that spectral components which were given as input were preserved and amplified spontaneous emission (ASE) was suppressed efficiently [15]. From the Eq. 5 it is clearly evident that the output optical power is dependent upon the carrier density of the medium, therefore on increasing the pump power the population of carriers increases instantly. Further these carrier decay to the sub-band emitting quantum of energy in the form of photons which transcends into amplification of the input wavelengths.

Figure. 5 input power spectrum

Figure. 6 Output Power at pump power 1W and HDF length 5m
The holmium doped fiber amplifier provides maximum gain of 51dB and 39.6dBm output power from -20dBm of input power. It is the highest power amplifier operated at atmospheric transmission window >2µm.

The performance of the holmium doped fiber amplifier is analysed by four parameters, bit error rate (BER), quality factor, extinction ratio (ER) and eye diagram. Bit error rate (BER) is the ratio of the percentage of error bits to the total number of bits received in a transmission (Alam et al.)[16].

Another performance parameter of the system is Quality factor. It is defined as:

$$Q = \frac{(P_1 - P_0)}{(\sigma_1 + \sigma_0)}$$  \hspace{1cm} (7)

Where, $P_1$ and $P_0$ are average power of output signals and $\sigma_1$ and $\sigma_0$ are standard deviations for ‘1’ and ‘0’. Higher value of the Q factor denotes the good system performance (Vanya et al.)[17].
Extinction ratio is also a performance parameter and it is the ratio of two optical powers, power of bit 1 to power of bit 0.

\[ \text{ER} = 10 \log_{10} \frac{P_1^{\text{min}}}{P_0^{\text{max}}} \]  

Where \( P_1^{\text{min}} \) and \( P_0^{\text{max}} \) are output peak power for bit 1 and bit 0. For better system performance the value of extinction ratio should be high. (Vanya et al. 2015)[17].

The BER, quality factor, Extinction ratio and eye diagram of the system at HDF length 5m, 9m and 11m and at wavelengths 2004nm and 2012nm are shown in fig. 9, 10, 11, 12, 13, 14 and 15.

**Figure 9** BER at 2004nm wavelength (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)

**Figure 10** Q-factor at 2004nm wavelength (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)

**Figure 11** ER at 2004nm wavelength (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)
Figure. 12 Eye diagram at 2004nm wavelength (Red: 5W & 9m, Green: 10W & 11m)

Figure. 13 BER at 2012nm wavelength (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)

Figure. 14 Q-factor at 2012nm wavelength (Brown: 1W & 5m, Red: 5W & 9m, Green: 10W & 11m)
At 5m of HDF length and 2004nm of wavelength the reported BER is 4.994E-30. While keeping the length constant and changing the wavelength to 2012nm the BER is 1.29E-26. On increasing the length of HDF to 9m, the value of BER changes to 5.39E-29 at 2004nm wavelength and 4.23E-28 at 2012nm wavelength. On further increasing the HDF length to 11m the reported value of BER is 8.94E-31 at 2004nm and 5.69E-25 at 2012nm wavelengths respectively. From Fig. 9 and 13 it is clear that on increasing the HDF length the BER gives minimum value for both the wavelengths. Lower BER reduces the chances of error occurring. Although in the proposed design the decrease in the value of BER on increasing the length is not constant but its value is way above the required standards for a good communication system which is 10E-12[6].

The Q-factor of the system is recorded to be 11.9dB with minor fluctuation on varying the length of HDF. From the eq 7 it can be deduced that Q factor is depended upon the difference of power of output signals, so if the difference is higher the value of Q-factor is high. On varying the length of HDF, Q-factor is almost constant. Value of extinction ratio in this system is approximately 18dB. Some fluctuations in ER is observed if the length of HDF is varied. The eye diagram of this system is much clear if the value of HDF length is high. The eye opening is very narrow and unclear at 5m of HDF length. When the length is increased the eye opening has widened with respect to the eye diagram for 5m of HDF length. Again on increasing the length of HDF to 11m the eye diagram plot is much better and the jitters are reduced considerably in this system.

VI. CONCLUSION

We have investigated holmium doped fiber amplifier with DWDM system, the wavelength spectrum is 2000nm-2012nm under different pumping power. The pump wavelength 1950nm is used
in this system. The length of holmium doped fiber was varied with pumping power. The maximum gain 51dB was achieved and maximum amplified output power 39dBm was obtained at 10W pump power with 11m of fiber length. The gain obtained was always greater than 20dB for the entire range of wavelengths, pump powers and fiber lengths. Performance of the holmium doped fiber amplifier was analysed by BER, Q-factor, ER and eye-diagram. Minimum BER was 8.94E-31 maximum value of Q-factor was 11.9dB. Maximum ER recorded was 18dB.

VII. ACKNOWLEDGMENTS

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REFERENCES

[1] A.D. Ellis et al., Approaching the non-linear Shannon limit, Journal of Light Technolgy, 28, pp. 423-433, 2010.
[2] H. Zhang et al., 81Gbps WDM transmission at 2µm over 1.15km of low loss hollow core photonic band gap fiber, ECOC, 2014.
[3] F. Poletti et al., Towards high capacity fiber optic communications at the speed of light in vacuum, Nat. Photonics 7, pp. 279-284, 2013.
[4] X. Jin, Z. Lou, Y. Chen, P. Zhou, H. Zhang, H. Xiao, Z. Liu, High-power dual- wavelength Ho-doped fiber laser at>2µm fiber laser, Scientific Reports 7, pp. 1-7, 2017.
[5] N. Simakov, Z. Li, Y. Jung, J.M.O. Daniel, P. Barua, P.C. Shardlow, S. Liang, J.K.S. Sahu, A. Hemming, W.A. Clarkson, S. Alam, D.J. Richardson, High gain holmium-doped fiber amplifiers, Optics Express 24, 2016.
[6] A. Hemming, N. Simakov, J. Haub, A. Carter, A review of recent progress in holmium doped silica fibre sources, Optical Fiber Technology 20, pp. 621-630, 2014.
[7] J.M. Senior, Optical Fiber Communications, Pearson.
[8] V.A. Kamynin, V. Tsvetkov, O.I. Medvedkov, A.S. Kurkov, Gain spectrum of the Ho-doped fiber amplifier, Laser Physics Letters 12(9), 2015.
[9] N. Simakov, Z. Li, P.C. Shardlow, J.M.O. Daniel, D. Jain, J.K. Sahu, A. Hemming, W.A. Clarkson, D.J. Richardson, Holmium-doped fiber amplifier for communications at 2.05-2.13µm, OSA, 2015.
[10] A. Hemming, N. Simakov, J. Haub, A. Carter, A review of recent progress in holmium doped silica fibre sources, Optical Fiber Technology 20, pp. 621-630, 2014.
[11] C.C. Baker, E.J. Friebele, A. Burdett, D.L. Rhonehouse, J. Fontana, W. Kim, S.R. Bowman et al., Nanoparticle doping for high power fiber lasers at eye-safer wavelengths, OSA 25(12), pp. 13903-13914, 2017.
[12] N. Simakov, A. Hemming, W.A. Clarkson, J. Haub, Carter, A., A cladding pumped, tunable holmium doped fiber laser, Optic Express 21(23), pp. 28415-28422, 2013.
[13] P. Peterka, B. Faure, W. Blanc, M. Karasek, B. Dussardier, Theoretical modelling of S-band thulium-doped silica fiber amplifiers, Optical and Quantum Electronics 36(1-3), pp. 201-212, 2004.
[14] C.R. Giles, E. Desurvire, Modelling erbium doped fiber amplifiers, Journal of Lightwave Technology 9(2), pp. 271-283, 1991.
[15] P. Honzatko, Y. Baravets, I. Kasik, O. Podracky, Wideband thulium-holmium doped fiber source with combined forward and backward amplified spontaneous emission at 1600-2300 nm spectral band, Optics Letters 39, 2014.
[16] S.M.J. Alam, M.R. Alam, G. Hu, M.Z. Mehrab, Bit error rate optimization in fiber optic communication, IJMLRC 1(5), pp. 435-441, 2011.
[17] V. Arun, N.K. Shukla, A.K. Singh, P. Singh, Design and performance analysis of multiple all optical logic gates in a single photonic circuit, Optical Quantum Electronics, 40, 2015.