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Efficient High GainYtterbium Doped Lead Fluoroborate Glasses Fiber Amplifiers

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Abstract

This paper is based on the numerical solution of the rate equations model and their gain dependences are discussed. Simulation of the amplifier gain versus the pump power, amplifier length, ion concentration and core radius has been done. In order to keep the fiber amplifiers doped with ytterbium as short as possible with high gain, it is best to increase the doped concentration. For 10m amplifier length, pump power of 25mW, core radius of 2.5μm and 3.5×10^{25}ion/m^3 doping concentration, the gain is 60dB. Increasing of the core radius would increase the threshold pump power and at the above same conditions, the optimum gain is at 5μm core radius.

Keywords: Ytterbium Doped Fiber Amplifier (YDFA), Single mode، Population inversion and Three-level rate equations.

مضخم ليف زجاج فلوروبورات الرصاص الكفوء عالي الربح المطعم بالاتربيوم

عبد الكريم حسين داغر جابر حسين الاسدي مؤيد جبار كريم

الخلاصة

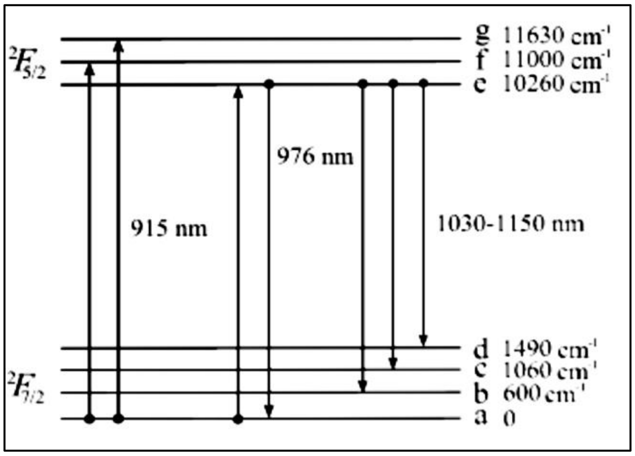
تمت مناقشة هذه الورقة التي تستند على الحل العددي لنموذج معادلات المعدل واعتماد الربح عليها. أجريت محاكاة لربح المضخم مقابل قدرة الضخ، طول المضخم، تركيز الايونات ونصف قطر اللب. لأجل أن نحفظ مضخم الليف المطعم بالاتربيوم قصيرا" قدر الامكان مع ربح عالي، من الافضل أن نزيد تركيز التطعيم. لمضخم طوله(10m) ، قدرة ضخ(25mW)، نصف قطر لب(2.5μm) وتركيز تطعيم (3.5x1025 ion/m3)، يكون الربح (60dB). زيادة نصف قطر اللب سوف يزيد من قدرة ضخ العتبة وعند نفس الشروط أعلاه، أفضل ربح يكون عند نصف قطر لب قدره (5μm).

Introduction

Fiber lasers and amplifiers have attracted great interest recently, because they offer the advantages of compact size, high gain, guided mode propagation and better stability [1]. Ytterbium doped fiber amplifier YDFA has a great potential because it does not have some of the drawbacks associated with erbium-doped amplifier: excited state absorption phenomenon that can reduce the pump efficiency and concentration quenching by intrinsic energy transfer do not occur, and high doping levels are possible [2]. Thus, it offers high output power (or gain) with a smaller fiber length moreover, excellent power conversion efficiency. YDFA's have a simple energy level structure and provide amplification over a broad wavelength range from 975 to 1200nm. YDFA's have great potential in many applications, including power amplification, sensing applications, free-space laser communications, and chirped-pulse amplification of ultra-short pulses [3].

Rate Equations Model

Ytterbium is a two level system having four Stark levels in the lower manifold 2F7/2 and three Stark levels in upper manifold 2F5/2, as shown in figure(1). Rate equations model which describe the gain and propagation characteristics of the Yb-doped fiber amplifier operating at 968 nm has been done. N1 and N2 are introduced as fractional densities of ions in the energy levels 2F7/2 and 2F5/2 respectively. In the initial condition there is no pump, N2=0 and Nt = N1.



Figure(1): energy level diagram illustrating the ytterbium ground $^2F_{7/2}$ and excited $^2F_{5/2}$ state manifolds and possible transitions between the sub-levels [4].

The following equations show the atomic transition for these ion populations [5,6]:

$$\frac{dN_1}{dt} = -W_{Sa}N_1 + W_{Se}N_2 + A_{21}N_2 - W_P N_1 \quad (1)$$

$$\frac{dN_2}{dt} = W_{Sa}N_1 - W_{Se}N_2 - A_{21}N_2 + W_P N_1 \quad (2)$$

where WP is the pump transition, Wsa , Wse is the signal transition for absorption and emission respectively and A21 is the spontaneous emission coefficient, the above factors can obtain by the following relations [4].

$$W_P(\nu_P) = \sigma_{Pa}\frac{I_P}{h\nu_P} \quad (3)$$

$$W_{Se}(\nu_s) = \sigma_e\frac{I_s}{h\nu_s} \quad (4)$$

$$W_{Sa}(\nu_s) = \sigma_a\frac{I_s}{h\nu_s} \quad (5)$$

IP, S represents the intensity of the pump and signal radiation.

$$I_i = \frac{P_i}{A} \quad , i= P, s \quad (6)$$

$$A_{21} = \frac{1}{\tau_{21}} \quad (7)$$

where σa and σe are the signal absorption and emission cross-sections, σPa is pump absorption cross section, νP and νS are the pump and signal frequencies, respectively, τ21 is the fluorescent lifetime of the excited state, Pi is the pump and signal power and A is the cross section area of fiber [7]. At steady state ($\frac{dN_i}{dt} = 0$), with some arrangements yields,

$$N_1 = \frac{W_{Se} + A_{21}}{W_{Sa} + W_P}N_2 \quad (8)$$

In order to obtain gain, the stimulated emission from state 2 to state 1 must be greater than the absorption from state 1 to state 2. This condition implies that the population in state 2 must be maintained at a greater level than that of state 1 i.e. population inversion, more than half the ground state atoms must be pumped into the meta stable state to achieve population inversion. The degree of population inversion is expressed by population inversion factor nSP and defined as [8]:

$$n_{sp} \equiv \frac{N_2}{N_2 - N_1\frac{\sigma_{Pa}}{\sigma_{Pe}}} \quad (9)$$

where (σPa/σPe) close to 1 for Yb+3. Substitute Eq.(8) and (7) into (9) yield

$$n_{sp} \equiv \frac{N_2}{N_2 - N_1} = \frac{W_P\tau_{21} + W_{Se}\tau_{21}}{W_P\tau_{21} + (W_{Sa} - W_{Se})\tau_{21} - 1} \quad (10)$$

Therefore, nsp is related to the pump and signal powers by WP and Ws respectively. The total ion density (Nt) is equal to [6]

$$N_t = N_1 + N_2 \quad (11)$$

The relative population inversion (ΔN/N) defined as [9]

$$\frac{\Delta N}{N_t} = \frac{N_2 - N_1}{N_t} \quad (12)$$

From Eqs.(8) and (11) we have

$$N_1 = \frac{W_{Se}\tau_{21} + 1}{W_P\tau_{21} + (W_{Sa} + W_{Se})\tau_{21} + 1}N_t \quad (13)$$

$$N_2 = \frac{W_{Sa}\tau_{21} + W_P\tau_{21}}{W_P\tau_{21} + (W_{Sa} + W_{Se})\tau_{21} + 1}N_t \quad (14)$$

Subtract Eq. (13) from (14) with the aid of (12) we get:

$$\frac{\Delta N}{N_t}=\frac{N_2-N_1}{N_t}=\frac{W_P\tau_{21}+(W_{Sa}-W_{Se})\tau_{21}-1}{W_P\tau_{21}+(W_{Sa}+W_{Se})\tau_{21}+1} \quad (15)$$

When the pumping rate is high enough, or WP >> Ws and WP>>1/τ21, $N_2-N_1\approx N_t$. In this case, the medium gain is approximately [10]:

$$g_\circ=(\sigma_e N_2-\sigma_a N_1)\approx\sigma_e N_t=g^* \quad (16)$$

where g∗ is the upper limit of the medium gain constant. The ratio emission-to-absorption cross sections of the signal wavelength may be defined as [11]:

$$\eta=\frac{\sigma_e}{\sigma_a} \quad (17)$$

From Eqs.(14) and (15) with the aid of (17) and the definition of g∗ given by Eq.(16), we get:

$$g_\circ=g^*\frac{W_P\tau_{21}+(W_{Sa}-\eta^{-1}W_{Se})\tau_{21}-\eta^{-1}}{W_P\tau_{21}+(W_{Sa}+W_{Se})\tau_{21}+1} \quad (18)$$

and from Eqs.(3) to (6) with (17), we get

$$W_p=\frac{\sigma_{Pa}p_P}{h\nu_p A} \quad (19)$$

$$W_{Se}=\frac{\sigma_e p_s}{h\nu_s A} \quad (20)$$

$$W_{Sa}=\frac{\sigma_a p_s}{h\nu_s A}=\frac{\sigma_e P_s}{\eta h\nu_s A} \quad (21)$$

The gain coefficient of a homogeneously broadened be written as [12]

$$g(w)=\frac{g_\circ}{1+(w-w_a)^2T_2^{\,2}+P/P_{sat}} \quad (22)$$

where g0 is the peak value, ω is the frequency of the incident signal, ωa is the atomic transition frequency and P is the optical power of the continuous wave CW signal being amplified. The saturation power Psat depends on doping parameters such as the fluorescence time T1 and the transition cross section σ. The parameter T2 in Eq.(18) is known as the dipole relaxation time and is typically quite small (0.1ps) for fiber amplifiers. Considers the amplification factor defined as G = Pout/Pin, where Pin and Pout are the input and output powers of the CW signal being amplified. The amplification factor is obtained by solving [13]

$$\frac{dP}{dz}=g(w)P(z) \quad (23)$$

where P(z) is the optical power at a distance z from the input end of the amplifier. A straight forward integration with the conditions P(0) = Pin and P(L) = Pout shows that the amplification factor for an amplifier of length L is given by [14]

$$G_\circ=G\,(w)=\exp(\int_0^L g(w)dz)=\exp[g(w)L] \quad (24)$$

where G is the unsaturated amplifier gain is assumed to be constant along the amplifier length. Both G(ω) and g(ω) are maximum at ω =ω a and decrease when ω ≠ ωa. However, G (ω) decreases much faster than g(ω) because of the exponential dependence. Substituting g from Eq.(23) in Eq.(22), to obtain

$$\frac{dP}{dz}=\frac{g_\circ P}{1+P/P_{sat}} \quad (25)$$

where g° is the small-signal gain coefficient at a given wavelength, P is the signal power, and Psat is the saturated signal power, defined as the power required for the gain to drop 3dB [4]. This equation can be easily integrated over the amplifier length. By using the initial condition P(0) = Pin together with P(L) = Pout = GPin , and by using Eqs.(18) and (22), the amplifier gain is given by the implicit relations after some manipulation [9,14]

$$\ln(\frac{P_{out}}{P_{in}})+\frac{1}{P_{sat}}(P_{out}-P_{in})=g_\circ L \quad (26)$$

$$G=G_\circ\exp\{-(G-1)\frac{P_{in}}{P_{sat}}\} \quad (27)$$

$$G_\circ=\exp(g_\circ L) \quad (28)$$

With the saturation signal power of [18]

$$P_{sat}=\frac{h\nu_s A}{(\sigma_a+\sigma_e)\tau_{21}}=\frac{\eta h\nu_s A}{(1+\eta)\sigma_e\tau_{21}} \quad (29)$$

Results and discussion

The following data (table) are used in simulation program for ytterbium doped lead flouroborate glass fiber amplifiers at 968 nm pumping wavelength.

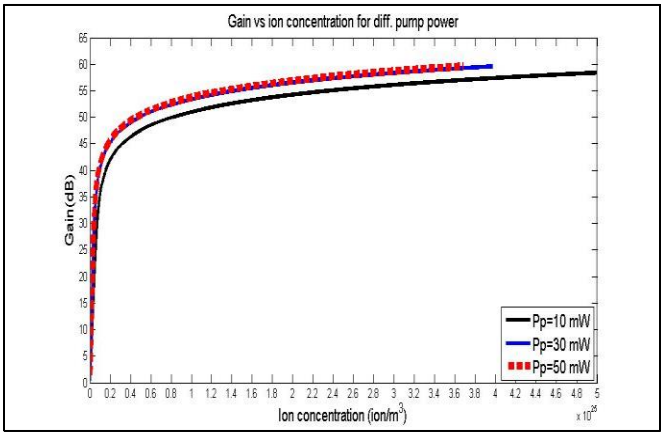
Table: Typical YDFA parameters, with ($^2F_{5/2} \rightarrow {}^2F_{7/2}$) transition Yb+3 doped lead flouroborate glass [13].

Symbol	Definitions	Value
σa	Pump absorption cross sections	2.56x10-24 m2
σe	Signal emission cross sections	1.07x10-24 m2
λs	Signal Wavelength	1022 nm
λp	Pump wavelength	968 nm
τ21	E2-E1 transition lifetime	0.81 ms
a	Core radius of the fiber	(2-10) μm
L	Length of the fiber	(2-15)m
pp	Pump power	(0-40) mW
ps	Signal power	1 μW
η	The ratio emission-to-absorption cross sections	0.65

The characteristics of the Yb+3 doped fiber amplifiers pumping at 968nm wavelengths can analyzed by employing an amplifier based on population of a classical model. The gain carve is exponentially increased with ion concentration and saturate after a certain level. The amplifier reaches population inversion, high concentration or long fibers are required to absorb efficiently the pump power. In long fibers, the absorption of the signal wavelength will reduce the efficiency of the amplifier, since the amplifier gain must first compensate the propagation losses. For this reason, we have chosen to increase the doping level to keep the fiber short and increasing a transition cross section. Figures 2, 3 and 4 represent the gain versus ion concentration; figure 2 shows that pumping powers 25 and 50mW has no deference which give approximately 60dB gain, so 25mW is the optimum value, figure 3 explains that any increase in fiber length means increase in gain but at the same time increasing length causes decreasing in ion concentration, in agreement with[14,15]. Figure 4 shows 5µm core radius gives efficient gain 60dB. Figures 5,6 and 7 demonstrate the gain with pump power; the threshold value of pump power can be determined, figure 5 shows that larger ion concentration means high gain but the threshold value of pumping power clamped at 2mW, in figure 6, 15m length reach 62dB with pumping power less than 4mW, in figure 7 when core radius is increased causes differ in threshold value of pump power, acceptance reference [16] in other side we can see that the gain value is from 60 to 62 dB, therefore 2.5 - 5µm core radius are the optimum value. Figures 8,9 and 10 gain as a function of fiber length; as it clear from figure 8 increasing ion concentration meting by decreasing in fiber length, for 3.5x1025 ion/m3 and 4.5x1025 ion/m3 the gain is within the optimum value, over than 60dB, figure 9 make us sure that 25mW is the best value for such amplifier, as in [16], figure 10 shows that the highest gain 62dB for 5µm core radius with long fiber while 2.5µm core radius gives 60dB for short fiber. Figures 11, 12, and 13 amplifier gain as a function of core radius; figure 11 shows that for ion concentration 4.5x1025 ion/m3, the core radius must be larger than 0.4µm, the gain curve is appear with gain value larger than 60dB, for all ion concentration the gain curves after 10µm are dropped sharply to zero value because of pump power 25mW cannot excite ions at 10m length and 11µm core radius, while in figure 12, 50mW pump power can excite ions at fiber length of 10m and core radius larger than 10µm and gain value is stayed within the optimum value lager than 60dB, figure 13 shows that 4-7µm core radius is optimum value for 10m length, 25mW and 3.5x1025 ion/m3.

Conclusion

According to the results, it was clear that the pump power applied to YDFA sharply reduces due to efficient absorption ytterbium ion. Amplifier gain is strongly dependent on the fiber length, pumping power, ion concentration and core radius. It is possible to design amplifiers of large gain with few meter length and high ion concentration and vice versa. Any increase in the fiber core radius would increase the threshold pump power.



Figure(2): Gain vs. ion concentration at diff. pump power of (YDFA), L=10m, λp=968nm, λs=1022nm, a=2.5μm.

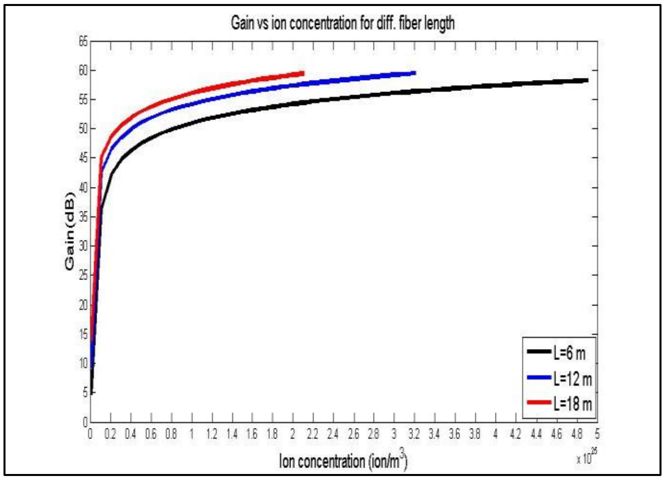


Figure (3): Gain vs. ion concentration at diff. fiber length of (YDFA), pp=25 mW, λp=968nm, λs=1022nm, a=2.5um.

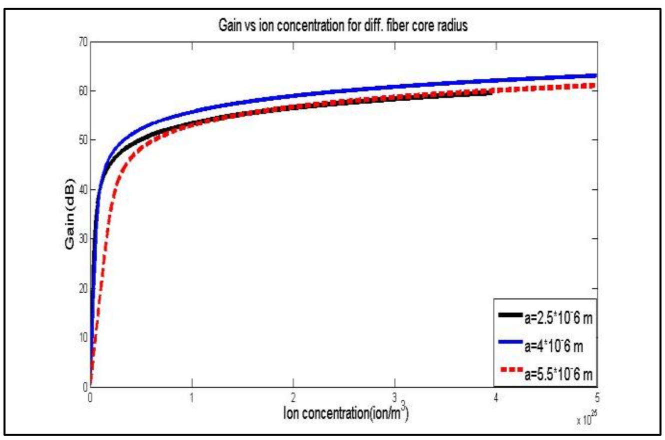


Figure (4): Gain vs. ion concentration at diff. core radius of (YDFA), L=10m, λp=968nm, λs=1022nm, pp=25 mW.

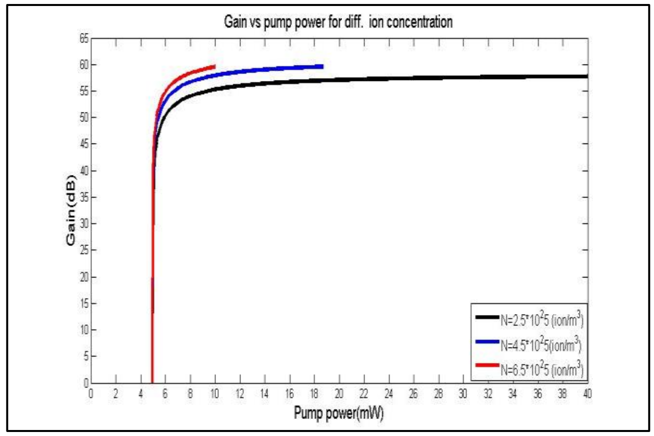


Figure (5): Gain vs. pump power at diff. ion concentration of (YDFA), L=10m, λp=968nm, λs=1022nm, a=2.5μm.

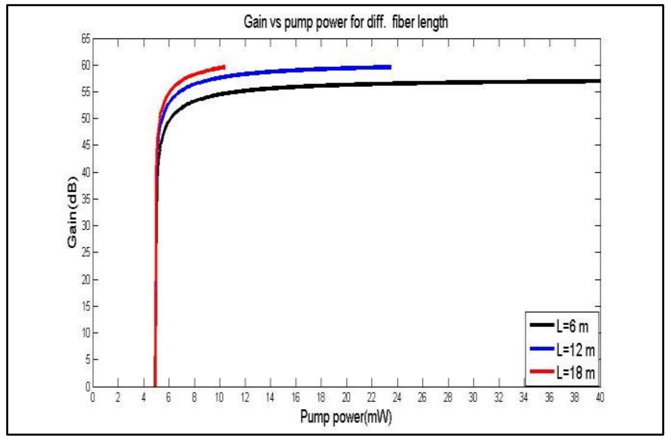


Figure (6): Gain vs. pump power at diff. fiber length of (YDFA), λp=968nm, λs=1022nm, a=2.5μm, N=3.5x1025 ion/m3.

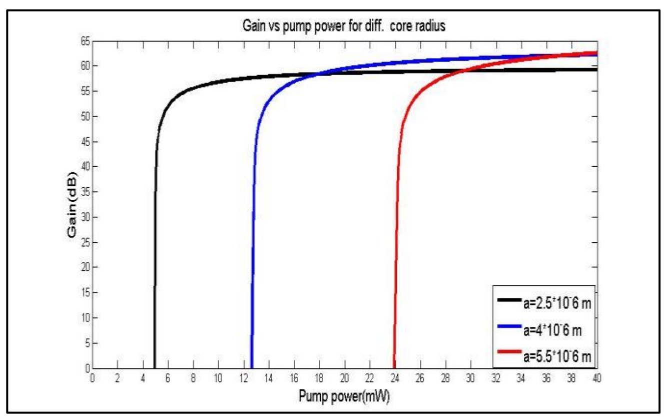


Figure (7): Gain vs. pump power at diff. core radius of (YDFA), L=10m, λp=968nm, λs=1022nm, N=3.5x1025 ion/m3 .

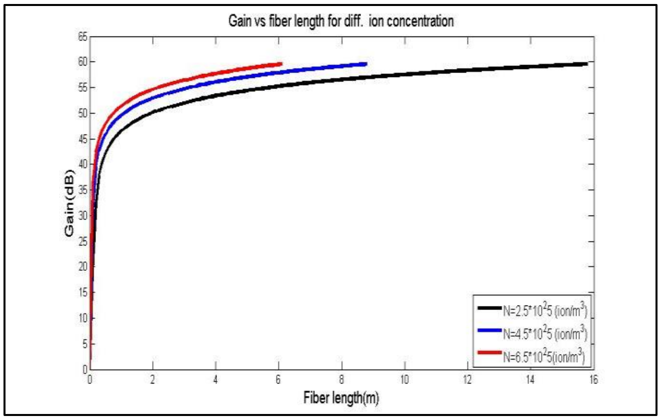


Figure (8): Gain vs fiber length at diff. ion concentration of (YDFA), pp=25 mW, λp=968nm, λs=1022nm, a=2.5um.

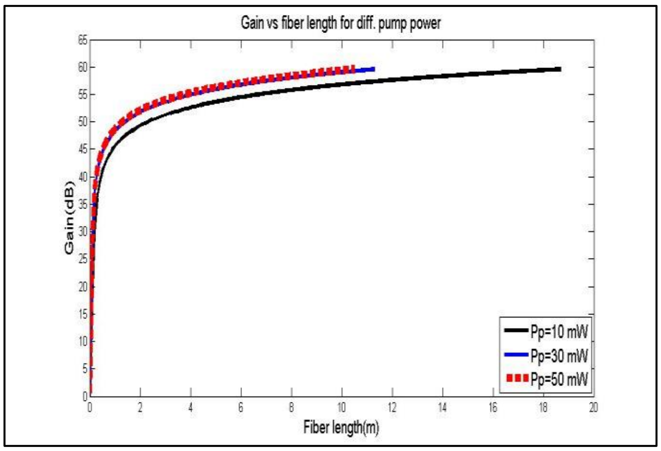


Figure (9): Gain vs. fiber length at diff. pump power of (YDFA), λp=968nm, λs=1022nm, a=2.5μm, N=3.5x1025 ion/m3.

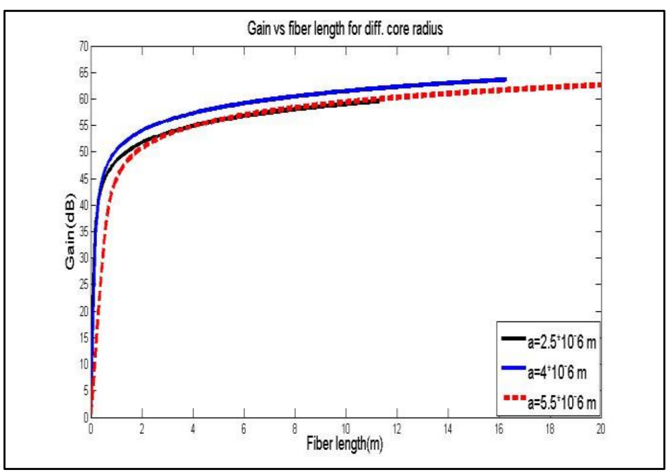


Figure (10): Gain vs. fiber length at diff. core radius of (YDFA), pp=25 mW, λp=968nm, λs=1022nm, N=3.5x1025 ion/m3.

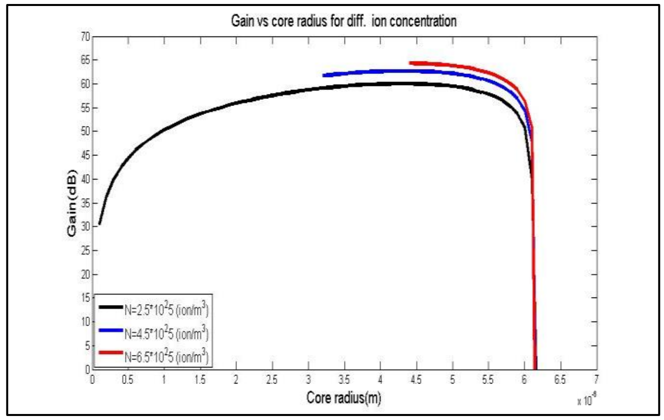


Figure (11): Gain vs core radius at diff. ion concentration of (YDFA), L=10m, λp=968nm, λs=1022nm, pp=25 mW.

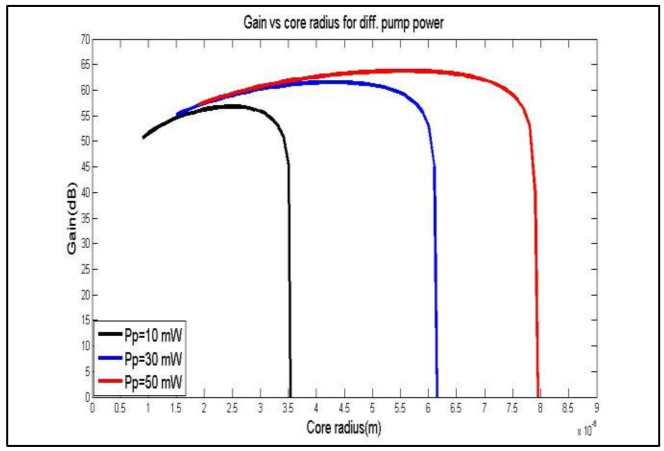


Figure (12): Gain vs. core radius at diff. pump power of (YDFA), L=10m, λp=968nm, λs=1022nm, N=3.5x1025 ion/m3.

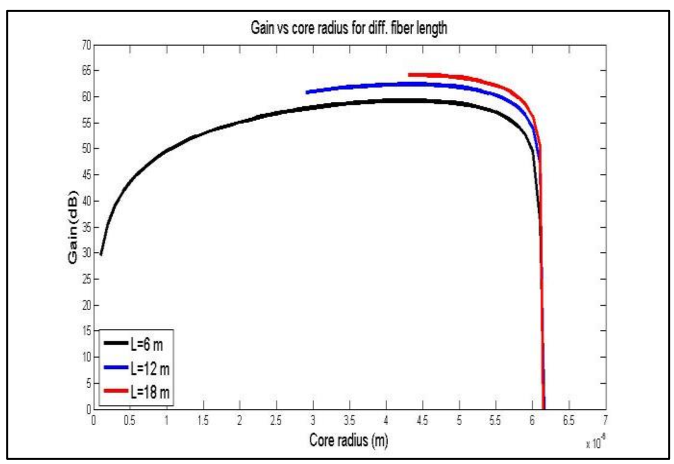


Figure (13): Gain vs. core radius at diff. fiber length of (YDFA), pp=25 mW, λp=968nm, λs=1022nm, N=3.5x1025 ion/m3.

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