Gain and Noise Figure of S-Band Tm-Doped Fiber Amplifiers Using Different Hosts

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Abstract Gain and noise figure spectra are modeled and investigated for the thulium doped fiber amplifier (TDFA). Four different hosts are examined; namely: silicate, chalcohalide, sulfide and heavy metal oxide. Amplifier gain and noise figure are studied with and without the amplified spontaneous emission (ASE). A comparative study is presented showing the effect of pump power, pump wavelength and thulium concentration is studied.

Keywords: Thulium doped fiber amplifier (TDFA), gain, noise figure, amplifier bandwidth.

1. Introduction

Optical fibers attenuate light during propagation like any other material .In Case of silica fibers, the attenuation constant is quite small, particularly in the wavelength range 1.0-1.6 µm where it is typically less than 1 dB/km with the minimum value of about 0.2 dB/km occurring near 1.55 µm. In long–haul fiber–optic communication systems, where transmission distances are about 100 km and may exceed thousands of kilometers for undersea lightwave systems, this attenuation cannot be ignored. In practice, loss limitations are overcome by periodic generation of the optical signal at repeaters.

The optical amplifier, in principle, provides a much simpler solution in that it is a single in – line component which can be used for any kind of modulation at virtually any transmission rate. Moreover , such a device can be bidirectional and if it is sufficiently linear it may allow multiplex operation of several signals at different optical wavelengths (i.e. wavelength division multiplexing) in particular with single – mode fiber system , the effects of signal dispersion can be small and hence the major limitation on repeater spacing becomes attenuation due to fiber losses.

The technique of doping silica fibers with rare-earth elements constitutes a relatively new technology that be used to make fiber lasers and amplifiers.

Characteristics such as the operating wavelength and the gain bandwidth are determined by dopants rather than by fiber, which play the role of a host medium these doped fibers amplify incident light through stimulated emission, the same mechanism used by lasers.

Rare earth ions, more specifically bivalent or trivalent lanthanides, have been used as activators in as many as 425 known laser crystals, most of which have an ordered structure. In these crystalline hosts, the most frequent rare earths observed to yield stimulated emission are Nd (neodymium). Ho (Holmium), Er (erbium), and Tm (Thullium). The different types of laser glasses can be grouped into four main categories: oxide, halide, oxyhalide, and chalcogenides .

A comprehensive numerical model of a thulium-doped silica-based fiber amplifiers is studied by P. Peterka et al. [1]. While, a model for 455-nm thulium-doped fluorozirconate fiber lasers co-pumped at 645 nm and 1064 nm is presented by F. Brunet et al. [2]. T. Kasamatsu described in detail the amplification characteristics of gain-shifted thulium doped fiber amplifiers operating in the 1480-1510nm wavelength region for the use of WDM systems. Absorption and emission properties between 350nm and 1600nm of the Tm^{3+} ions in optical fibers were investigated using the Tm^{2+}-Tm^{3+} codoped germanosilicate glass fibers and its fiber perform by Y.H. Kim et al. [3]. In Ref. [4] Y.S. Han investigated the 1.48 µm emission properties and the cross-relaxation mechanism of Tm^{3+} ions in $0.7(Ge_{0.25}As_{0.10}S_{0.65})$ + $0.15GaS_{1.5}$ + 0.15CsBr glass. Both the relative intensity ratio of the 1.48 µm emission to 1.82 µm and the measured lifetime of the $^3H_4$ level decreased with increasing Tm^{3+} concentration. Heavy metal oxide glasses containing GeO_2 were investigated as potential hosts for 1.48 μm fiber-optic amplifiers because of their low phonon energy [5].

Section 2 describes the mathematical model and analysis used to calculate the amplifier gain and analysis. The results are given in Sec. 3, including the gain and noise figure spectra and the effect of pumping power on both spectra with and without the consideration of the amplified spontaneous emission (ASE). This is followed by the conclusions in Sec. 4.

2. Model and Analysis

2.1 Amplifier Gain Calculations

The amplifier gain coefficient, g, is defined by [6]:

$$g = \sigma_{ul} N\left[n_u - \frac{w_u}{w_l} n_l \right]. \quad (1)$$

where n_u and n_l are the electron concentration in the higher and lower lasing levels, respectively. Here σ_{ul} is the stimulated emission cross section, w_i is the statistical weight of the ith level, and the electron transition occurs between the upper level with i = u and the lower level with i = l separated by an energy difference E_{ul} = hv.

If several energy levels are separated by an equal distance, hv, then a summation over all such levels will be:

$$g(v) = \sum_{E_i - E_j = hv} \sigma_{ij} N\left[n_i - \frac{w_i}{w_j} n_j \right]. \quad (2)$$

A continuous level density approximation is used to describe each Thulium ion manifold. The temperature dependence of a TDFA is mainly due to the variation in the occupation probability density within each manifold. In particular, the relative occupation of two levels in thermal equilibrium follows Boltzmann's law. The most general form of the probability function, probability of occupation with electrons , P(E) is:

$$P(E) = e^{-(E/KT)} \cdot f(T) \ . \quad (3)$$

Here f(T) is an arbitrary function of temperature.

Suppose that there are two identical manifold u and l, then:

$$P_u(E) = \exp(-\frac{E - \Delta E}{KT}) \cdot f_u(T) , \quad (4)$$

and

$$P_l(E) = \exp(-\frac{E}{KT}) \cdot f_l(T) \ . \quad (5)$$

Equation (2) can be transformed for a continuous thulium ion spectrum by changing the summation an integration over E, and substituting ρ(E+hv)/ρ(E) for w_i/w_j, where ρ(E) is the energy density of state or mainflod(E).

$$g(v) = \int_0^\infty \sigma(E + hv, E)\, N\, [\rho(E + hv)\, P(E + hv) - (\rho(E + hv)/\rho(E))\, \rho(E)\, P(E)] dE \ . \quad (6)$$

When the upper manifold is occupied, the equation yields:

$$g(v) = g^*(v)$$

$$= N \int_0^\infty \sigma(E + hv, E)\, \rho(E+hv)\, P_u(E+hv)\, dE \ . \quad (7)$$

For occupied low manifold (7) gives

$$g(v) = -\alpha = -N \int_0^\infty \sigma(E+hv, E)\, \rho(E+hv)\ P_l(E)\, dE. \quad (8)$$

Here P_u and P_l stand for distributions for upper and lower manifold occupied, respectively, substitution of (4) and (5) into (7) and (8) gives expression for absorption and emission coefficients α and g^*:

$$\alpha(v) = N\ f_l(T) \int_0^\infty \sigma(E+hv, E)\ \rho(E+hv)\ \exp(-\frac{E}{KT}) dE \ , \quad (9)$$

$$g^*(v) = N\ f_u(T)\ \exp(\frac{\Delta E - hv}{KT}) \cdot \int_0^\infty \sigma(E+hv, E)\ \rho(E+hv)\ \exp(-\frac{E}{KT}) dE \ . \quad (10)$$

Combining (9) and (10) gives the McCumber's relation as:

$$g^*(v) = \alpha(v) \ . \ \exp(\frac{\Delta E' - hv}{KT}) , \quad (11)$$

$$\Delta E' = \Delta E + \ln(\frac{f_u(T)}{f_l(T)}) , \quad (12)$$

Thulium-doped fiber amplifier gain can be expressed via these parameters by [6]:

$$G(v,Inv) = \frac{1}{p(v)} \cdot \frac{dp(v)}{dz}$$
$$= [\, g^{*}(v) + \alpha(v)\,]\, Inv - \alpha(v) - L(v)\,, \qquad (13)$$

where L(v) is the background loss of the fiber and Inv is the local inversion of thulium ions.

2.2 Noise Figure Calculations

For noise figure calculations, a full description was presented in Refs. [7 and 8]. Noise figure, F, is closely related to the spectral intensity of the forward propagation, as well as the amplifier gain. Base on Ref. [8], the noise figure, F, can be obtained as:

$$F = \eta_{sp}\,((g-1)/G)\,, \qquad (14)$$

where G is the gain in linear units, η_{sp} (= $n_2/(n_2-n_1)$) is the spontaneous-emission factor , n_1 and n_2 are the population of the lower and upper lazing levels, respectively.

3. Reults and Discussion

3.1 Introduction

The following in the amplifier performance at 1.05, 1.05-1.56 and 1.4-1.56 µm pumping schemes on different host materials doped with Tm^{+3} ions. We will basically focus on the small signal gain and noise figure spectra for single stage TDFA. Models described in Refs. [9 and 10] are used to calculate the fractional inversion factor (Inv) which is the key for gain and noise figure calculations. Forward propagation analysis only was taken in consideration to give flexibility in choice of pump power and their wavelengths and reduce the complexity generated in dual-pumping schemes. A full S/S^{+} band (1450-1530nm) was considered for full description about the effects of ASE and losses on the amplifier performance.

3.2 TDFA Small signal, single stage gain spectrum for 1.05, 1.05-1.56 and 1.4-1.56 µm pumping schemes in silicate fibers

All spectroscopic data, branching ratios, fiber design parameters and absorption with emission cross sections are extracted from Ref. [10] for thulium doped silicate fiber amplifier. A 7m long thulium-doped silicate fiber with Tm^{+3} concentration Nt ~ 1.56×10^{25} cm^{-3} were assumed in our simulation. The input signal power is 10µw.The pump power at 1.05 and 1.4 µm (main pump source) was maintained at 1000mw while the power of auxiliary pump source at 1.56 was maintained to ~ 100mw (10% of the main pump power).

The small signal gain profile as a function of signal wavelength for the mentioned pumping schemes in thulium doped silicate fiber amplifier is shown in Fig.1.

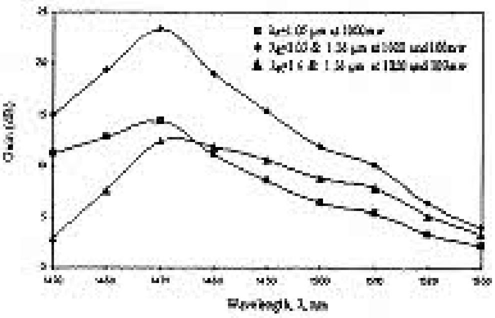

Fig.1 Small signal single stage gain spectrum for 1.05, 1.05-1.56 and 1.4-1.56 µm pumping schemes.

For the 1.05µm pumping (filled squares) a maximum gain of ~ 15db in the region 1465-1470 nm was obtained. A decrease was observed after the peak to reach ~ 2.5 db at 1530. As similar to thulium doped fluoride fiber amplifier in small signal regime, gain obtained by us is grater in a degree of 1-3 db over WDM application obtained by P. Peterka et al. [10]. This is mainly because the small signal operation does not suffer the saturation of the amplifier obtained in WDM systems. This can be treated through refinements of amplifier design regarding to different amplifier parameters. For 1.05-1.56 µm pumping (filled circles) a maximum gain of ~ 23.5 db was obtained at exactly 1470 nm and for 1.4-1.56 µm pumping (filled triangles) a maximum gain of ~12.5 db was obtained in the region of 1470-1475 nm, while a uniform decrease was observed after this peak until reaching ~ 3.3 db at 1530. This behavior coincides with that obtained in Ref. [9], where all fractional inversion near 0.7 provides an S^{+} -band gain profile (normal TDFA). The results also indicate (as TDFFAs) that dual-wavelength pumping utilizes thulium ions more efficiently than upconversion pumping, leading to gain enhancement.

3.3 Small Signal Single Stage noise figure spectra for 1.05, 1.05-1.56 and 1.4-1.56 μm pumping scheme

Based on the described model and gain spectrum, the small signal noise figure spectrum was calculated and the obtained results are displayed in Fig. 2.

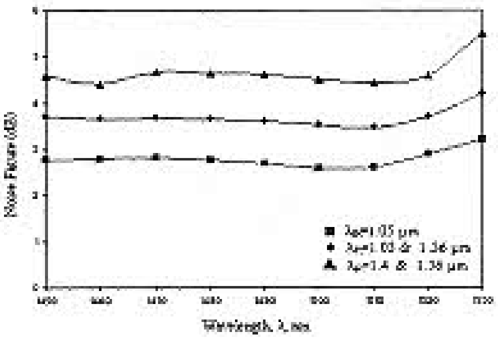

Fig.2 Small signal single stage noise figure spectrum for 1.05, 1.05-1.56 and 1.4-1.56 μm pumping schemes.

For 1.05 μm upconversion pumping scheme, an average value of about 3 db was calculated in studied spectrum except (1510-1530 nm). This very low calculated value of noise figure is similar to that calculated for TDFA by Tadashi Kasamatsu et al. [9].This is because the very high fractional inversion obtained in such pumping. For 1.05-1.56 μm pumping scheme an aveage value of about 3.7 dB was calculated in the whole spectrum except (1515-1530 nm). The increase in noise figure in the last band was smoother than 1.05 μm pumping scheme. For the 1.4-1.56 μm pumping scheme, an average value was calculated to be 4.7 db in the whole region except (1520-1530 nm).

3.4 Effect of pumping power at 1.05μm

3.4.1 Including ASE at 800nm band:

Figure 3 shows the small signal single stage gain spectrum for different pump power (500, 1000 & 1500 mw) pumped at 1.05μm including ASE at 800nm band. It is clear that increasing pump power enhances power conversation efficiency, fractional inversion factor and improving the gain. A maximum gain is observed (~ 17 dB at 1470 nm) for 1500 mw pump power followed by ~11.5 dB for 1000mw and about ~ 7.7 dB for 500mw.

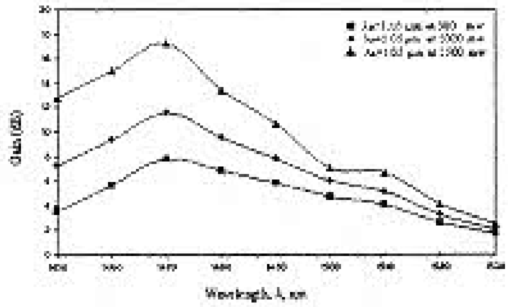

Fig.3 Small signal single stage gain spectrum for 1.05μm pumped with different pump power with ASE.

Figure 4 shows the noise figure spectrum for different pump powers at 1.05μm including ASE at 800 nm. As one can expect the highest noise figure of about 4.1 dB in average was calculated at 500m which corresponds to the lowest population inversion.

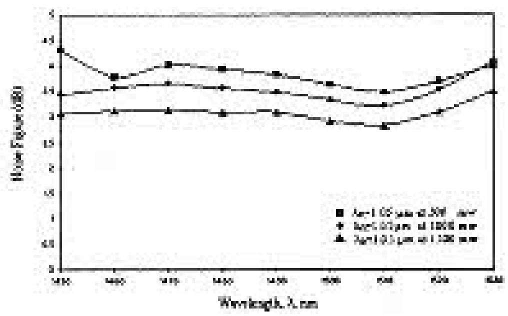

Fig.4 Small signal single stage noise figure spectrum for 1.05μm pumped with different pump power with ASE.

3.4.2 Suppressing ASE at 800 nm band:

Based on the previous description, we are going to present gain and noise figure characteristics while suppressing ASE at 800 nm.

We investigate this issue due its future application where it provides us with two advantages; first: suppressed ASE at 800 nm through optical band pass filter will enhance gain and lower noise figure, second: we suggest using such suppressed power to help pumping in multistage amplification in WDM systems like that described in Refs. [11-13].

Figure 5 shows the small single stage gain spectrum for 1500, 1000, 500 mw but with suppressed ASE at 800 nm. Suppressing ASE results in enhancing the maximum gain of 1500 mw by 1.2 dB to reach ~ 18 dB at 1470nm, gain of 1000 mw pumping power by 3.5 dB to reach 15.2 dB at 1470 nm and gain of 500mw by 8.7 dB at 1470 nm.

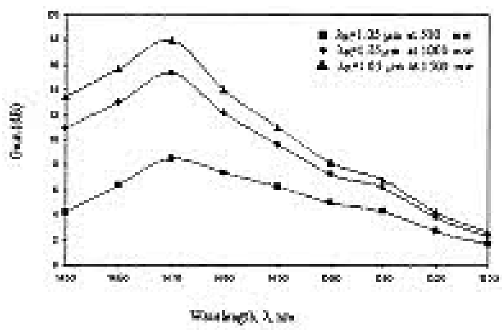

Fig.5 Small signal single stage gain spectrum for 1.05μm pumped with different pump power when suppressing ASE at 800nm.

Figure 6 shows the small signal single stage noise figure spectrum at the same pumped power and operation conditions as previously discussed. An average decrease of about 1.5 dB is obtained when the ASE is suppressed.

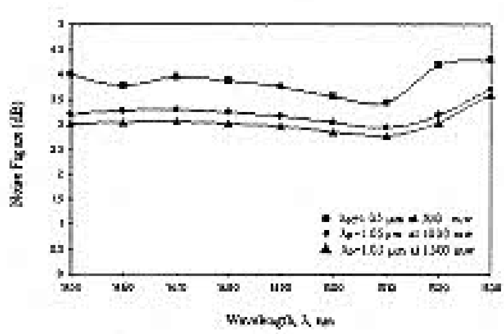

Fig.6 Small signal single stage noise figure spectrum for 1.05μm pumped with different pump power when suppressing ASE at 800nm.

3.5 TDFA Gain and noise figure for the hosts: chalcohalide, sulfide and heavy metal oxide.

The previous procedure is repeated for three other different hosts; namely: halcohalide, sulfide and heavy metal oxide. All spectroscopic data, branching ratios, fiber design parameters and absorption with emission cross sections are extracted from Ref. [14] for thulium doped heavy metal oxide amplifiers. While for sulfide and chalcohalide, the parameters are collected from Refs. [9 and 15]. The calculations are performed at the same values of pump power and pump wavelength. A similar behavior like that of the silicate host is obtained for the three hosts mentioned but with different values. The obtained results are summarized in Table 1. In this table, λ_{pump} is the pump wavelength, P_{pump} is the pump power, ρ is the optimal Tm^{+3} concentration, G_{max} is the maximum gain, λ_{max} the corresponding wavelength, BW the 3 dB bandwidth and F_{av} is the average noise figure.

4. Conclusion

The gain and noise spectra of the thulium doped fiber amplifier (TDFA) are investigated using four different hosts. Suppressing the amplified spontaneous emission (ASE) results in enhancing both the maximum gain and the noise figure. The obtained results are summarized in Table 1, from which one can get the best choice according to what with he is concerned (gain, bandwidth or noise figure).

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Host	Silicate			Chalochalide			Sulfide			Heavy metal oxide		
λ_{pump}(μm)	10.5	1.05-1.56	1.4 1.56	10.5	1.05-1.56	1.4 1.56	10.5	1.05-1.56	1.4 1.56	10.5	1.05-1.56	1.4 1.56
P_{pump}(mW)	1000	1000 &100	1000 &100	250	300 & 20	100 &40	250	300 & 20	100 &40	250	300 & 20	100 &40
ρ (Mol%)	-			0.2			0.2			0.25		
G_{max} (dB)	15	23.5	12.5	16	27.3	19.6	16.6	28	23	23.5	30	29
λ_{max} (nm)	1470			1480			14800			1480		
BW (nm)	25	20	33	25	21	30	30	25	20	30	13	17
F_{av} (dB)	3	3.7	4.7	3.26	3.7	4.5	3.4	3.7	4.4	3.5	4.2	4.6

Table 1 TDAF characteristic for different hosts

Gain and Noise Figure of S-Band Tm-Doped Fiber Amplifiers Using Different Hosts

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الملخص العربي

من التحديات الرئيسية التي تواجه منظومات الاتصالات البصرية محاولة تقليل أو تعويض فقدان الطاقة الذي يؤدي إلى ضعف الإشارة والناتج عن مسارها في الألياف البصرية. والحل العملي للتغلب على هذا الفقد والذي يحد من أداء هذه المنظومات هو معيدات التضخم أو المكبرات، حيث توضع هذه الأجهزة على طول الليف البصري لكشف الإشارة وتكبيرها بحيث لا تضعف الإشارة عن المستوى الكافي لقراءة واستخلاص البيانات منها. وفي بداية الأمر كانت هذه المعيدات أو المكبرات إلكترونية ولكنها كانت تعاني من مشاكل كثيرة أهمها أنها معقدة التركيب ولا خطية، كما أنها مرتفعة التكاليف وسرعة هذه المنظومات بطيئة مقارنة بالأنظمة الأخرى. نتيجة للعوامل السابقة فقد تطور القطاع البحثي الخاص بدراسة وتطوير أجهزة بديلة تستطيع تكبير الإشارات الضوئية دون تحويلها لأشكال أخرى.

وقد تم تكريس هذا العمل لدراسة هذا النوع من المكبرات و التي تستخدم الألياف البصرية المشابة بالعناصر النادرة (Lanthanides) وخاصة عنصر الثوليوم والمزودة بالطاقة من ليزر شبه الموصل، ويعمل هذا المكبر في المدى (1450-1530 μm)).

ويشمل البحث دراسة أنواع مستحدثة من المواد المضيفة لعنصر الثوليوم. كمادة السيلكا وأيضا مواد أخرى مثل مركبات Heavy metal oxide, Sulfide , Chalcohalide. يبدأ البحث بدراسة مادة السليكا كمادة مضيفة لعنصر الثوليوم (ثم يدرس المواد الأخرى) كما يتناول خواص المكبر البصري في هذه الحالة من حيث معامل الكسب وعامل الضوضاء وتأثير نسب الضخ المختلفة وأشكالها آخذين في الاعتبار الانبعاث العفوي المكبر (amplified spontaneous emission) في إحدى الحالات (السليكا) فقط حيث البيانات المنشورة متاحة فيها دون غيرها.