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Comparison of ASE Spectrums of Single Pass and Double Pass Er, Yb, Er-Yb Doped Fiber Amplifiers

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Kendiliğinden yükseltilmiş yayılma
EDFA
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EYDFA
Tek geçiş
Çift geçiş

Graphical/Tabular Abstract (Grafik Özet)

In the study, single pass and double pass amplifier systems were compared with dual port optical analyzer. By adding EDF, YDF, EYDF to the doped fiber block, single and double pass arrangements were examined. /Çalışmada tek geçişli ve çift geçişli yükselteç sistemlerinin dual port optic analizörle karşılaştırmaları yapılmıştır. Katkılı fiber blokuna EDF, YDF, EYDF ekleyerek tek ve çift geçişli düzenekler halinde incelemer yapılmıştır.

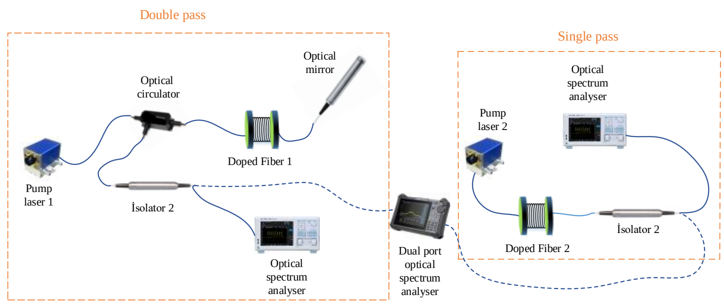

Figure 2: *Single-pass and double-pass schemes /* ***Şekil 2:*** *Tek geçişli ve çift geçişli düzenek*

Highlights (Önemli noktalar)

- *Analyses of EDFA, YDFA and EYDFA setups were carried out by taking the equations obtained from the erbium energy band level as an example. /Erbiyum enerji bant seviyesinden elde edilen denklemler örnek alınarak EDFA, YDFA ve EYDFA düzeneklerinin analizleri yapılmıştır.*
- *Single- and double-pass setups were analyzed separately for each fiber type/ Tek ve çift geçişli düzenekler herbir fiber türü için ayrı ayrı analiz edilmiştir.*
- *ASE spectra obtained in EDFA, YDFA and EYDFA setups were analyzed. / EDFA, YDFA ve EYDFA setuplarında elde edilen ASE spektrumları analiz edilmiştir.*

Aim (Amaç): *In the study, the ASE values of EDFA, YDFA and EYDFA doped optical amplifiers in single and double pass setups were examined and the setup with higher ASE values was shown in graphs. / Çalışmada EDFA, YDFA ve EYDFA katkılı optik yükselteçlerin tek ve çift geçişli düzeneklerde ASE spektrumları incelenmiştir ve hangi düzenekte ASE değerinin daha yüksek olduğu grafiklerde gösterilmiştir.*

Originality (Özgünlük): *The originality of the study is that ASE spectra for EDFA, YDFA and EYDFA are optimized and obtained and compared in single and double pass setups. / EDFA, YDFA ve EYDFA için ASE spektrumlarının optimize edilerek tek ve çift geçişli düzeneklerde elde edilmesi ve kıyaslanması çalışmanın özgünlüğüdür.*

Results (Bulgular): *The ASE value for EDFA was 0 dBm in the double-pass setup and -6 dBm in the single-pass setup, while for YDFA these values were 11 dBm at 975.3 nm and -17 dBm at 976 nm in the double-pass and single-pass setups, respectively, and 4.84 at 1560 nm and -14 dBm at 1568 nm in the double-pass and single-pass setups in EYDFA, respectively. /EDFA için ASE değeri çift geçişli düzenekte 0 dBm ve tek geçişlide -6 dBm, YDFA için bu değerler çift geçişli ve tek geçişli de sırasıyla 975.3 nm'de 11 dBm vw 976 nm'de -17 dBm oldu ve EYDFA'da çift geçişli ve tek geçişli düzeneklerde sırasıyla 1560 nm'de 4.84 ve 1568 nm'de -14 dBm olarak elde edildi.*

Conclusion (Sonuç): *As a result, higher ASE value was obtained in double-pass setups with the same amplifiers and the highest ASE value was obtained as 4.84 dBm in the C operating band at 1560 nm wavelength in the EYDFA setup./ Sonuç olarak, aynı yükselteçler ile çift geçişli düzeneklerde daha yüksek ASE değeri elde edildi ve EYDFA kurulumunda 1560 nm dalga boyunda C çalışma bandında en yüksek ASE değeri 4,84 dBm olarak elde edildi.*

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Abstract

In this study, the amplified spontaneous emission (ASE) spectra of Erbium (EDFA), Ytterbium (YDFA), and Erbium-Ytterbium (EYDFA) doped optical amplifiers were obtained in single-pass and double-pass simulation setups, compared and interpreted with each other. The spectra of the single-pass and double-pass setups of EDFA, YDFA, and EYDFA were compared using the ASE equations obtained at the Erbium energy level. The values applied in the single-pass and double-pass simulations, pump wavelength, pump power, amplifier length, and amplifier parameters, were assumed equally in both models. The pump wavelength for EDFA was 1480 nm, and the pump power was 1400 mW; the pump wavelength for YDFA was 960 nm, and the pump power was 800 mW, and these values were applied as 1025 nm and 1600 mW for EYDFA, respectively. The graphs at the output of the dual port spectrum analyzer showed that higher ASE values were obtained in the double-pass environment compared to the single-pass environment.

Tek Geçişli ve Çift Geçişli Er, Yb, Er-Yb Katkılı Fiber Amplifikatörlerin ASE Spektrumlarının Karşılaştırılması

Makale Bilgisi

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Öz

Bu çalışmada, Erbiyum (EDFA), İterbiyum (YDFA) ve Erbiyum-İterbiyum (EYDFA) katkılı optik yükselteçlerin güçlendirilmiş spontan emisyon (ASE) spektrumları tek geçişli ve çift geçişli simülasyon düzeneklerinde elde edilmiş, birbirleriyle karşılaştırılmış ve yorumlanmıştır. EDFA, YDFA ve EYDFA'nın tek geçişli ve çift geçişli kurulumlarının spektrumları, Erbiyum enerji seviyesinde elde edilen ASE denklemleri kullanılarak karşılaştırılmıştır. Tek geçişli ve çift geçişli simülasyonlarda uygulanan değerler, pompa dalga boyu, pompa gücü, yükselteç uzunluğu ve yükselteç parametreleri her iki modelde de eşit olarak kabul edilmiştir. EDFA için pompa dalga boyu 1480 nm ve pompa gücü 1400 mW idi; YDFA için pompa dalga boyu 960 nm, pompa gücü ise 800 mW olarak bulunmuş, bu değerler EYDFA için sırasıyla 1025 nm ve 1600 mW olarak uygulanmıştır. Çift portlu spektrum analizörünün çıkışındaki grafikler, çift geçişli ortamda, tek geçişli ortama kıyasla daha yüksek ASE değerlerinin elde edildiğini göstermiştir.

1. INTRODUCTION (GİRİŞ)

Optical sensing and communication systems are important in various applications in terrestrial, space, and submarine environments. However, integrating these systems poses several challenges, especially regarding energy sustainability and control [1-3]. Optical amplifiers are used to compensate for signal loss in optical systems. These amplifiers are classified according to various characteristics. The most used amplifiers are rare earth-doped fiber optic amplifiers. Erbium, Ytterbium, and Erbium-Ytterbium doped optical amplifiers are widely used due to their operating wavelengths and other properties [3-5].

Power attenuation and signal loss due to long distances in fiber optic transmission lines have been the subject of much research today. Increasing the

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signal power along the transmission line is the best solution, and various methods are used [6-8]. The most common and efficient of these methods are rare earth-doped optical amplifiers. Erbium, Ytterbium, and Erbium-Ytterbium doped optical amplifiers are widely used due to their operating wavelengths and other features [9-14].

In rare earth-doped fiber optic amplifiers, amplified spontaneous emission (ASE) is a noise generated by the pump signal applied to the system and in the amplifier energy band structure. The pump signal applied to the doped fiber causes the atoms of the element to move from the ground level to a higher level. Some of the atoms accumulated at the metastable level emit photons from themselves while descending to a lower level, and the emitted photon beams are called ASE. Since ASE emission does not have the same phase and characteristics as the input signal, it reduces the gain [10]. In general, ASE is a type of noise that occurs in optical laser sources, semiconductor optical amplifiers, and doped optical amplifiers. Still, more efficient optical amplifiers have been designed for certain wavelengths by optimizing the ASE value [15-30].

Broadband optical devices in the 1500–2100 nm wavelength range have recently attracted much research attention [21-24]. These devices include lasers, amplifiers, sensors, and optical sources. Optical sources can be based on doped fibers' enhanced spontaneous emission phenomenon. ASE sources are widely used in many applications, including medicine, imaging, and environmental monitoring through the detection of chemicals [10, 12].

In this study, ASE values of Er, Yb, and Er-Yb doped optical amplifiers were obtained and examined in single-pass and double-pass setups. In addition, absorption, emission, N_1 and N_2 graphs and values of the amplifiers were obtained.

In the second part of the study, information about the theory of EDFA will be given; simulation setups will be given in the third part. Finally, the results obtained from the study will be concluded in the fourth part.

2. EDFA THEORETICAL MODEL (EDFA TEORİK MODELİ)

For theoretical modeling of EDFA systems, equations obtained from Erbium energy band level facilitated doped fiber design, and the effects and characteristics of the parameters can be found. Therefore, in this study, Er3+ energy band level rate equations were first written, then equations for propagation equations and ASE were obtained.

2.1. Rate Equations (Oran Denklemleri)

Figure 1 shows the 2-level erbium energy band level. $^4I_{13/2}$ is level 2 and $^4I_{15/2}$ is level 1.

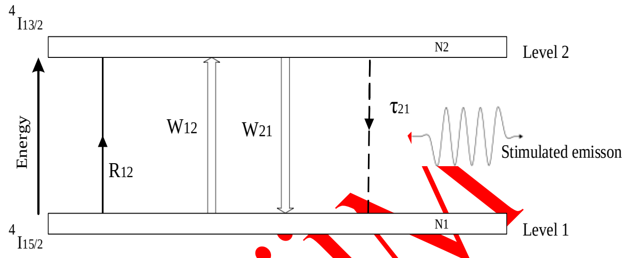

Figure 1. Erbium energy band levels (Erbiyum enerji bant seviyeleri)

$$\frac{dN_1}{dt} = -R_{12}N_1 - W_{12}N_1 + W_{21}N_2 + N_2/\tau_{21} \quad (1)$$

$$\frac{dN_2}{dt} = R_{12}N_1 + W_{12}N_1 - W_{21}N_2 - N_2/\tau_{21} \quad (2)$$

Here, the transition rate corresponds to the energy levels W_{ij} , N_i and N_j, and R_{ij} is the pump transition rate between N_i , N_j and [8]. Generally, τ_{21} is the stimulated emission lifetime and is radiative [9].

At the 1480 nm pump wavelength, the EDFA energy band level operates in 2 levels. Level 2 contributions are made only through the 1480 nm pump wavelength absorption cross-section from Level 1 to Level 2, as shown in Figure 1 [14]. This study performed EDFA simulation studies at 1480 nm pump wavelength.

2.2. Propagation Equations (Yayılım Denklemleri)

The dynamic propagation equations can be written as follows, with pump propagation at P_p wavelength of 1480 nm and signal propagation P_s at 1550 nm with EDFA length (L) and z-direction:

$$\frac{dP_p}{d_z} = -\Gamma_p P_p (N_1\sigma_{12(pa)} - N_2\sigma_{21(pe)}) - \alpha_p P_p \quad (3)$$

$$\frac{dP_s}{d_z} = -\Gamma_s P_s (N_1\sigma_{12(sa)} - N_1\sigma_{21(se)}) - \alpha_s P_s \quad (4)$$

In the above equations, P_p and P_s are the pump power and signal power, respectively, Γ_p and Γ_s are the pump and signal overlap factor, respectively, $\sigma_{12(pa)}$ is the pump absorption cross-sectional area, $\sigma_{21(pe)}$ is the pump propagation cross-sectional area, $\sigma_{12(sa)}$ is the signal absorption cross-sectional area, $\sigma_{21(se)}$ is the signal propagation cross-sectional area, α_p is the loss in pump signal wavelength and α_s is the loss in signal wavelength [13].

2.3. Amplified Spontaneous Emission (ASE) Equations (Kendiliğinden Yükseltilmiş Yayılma (ASE))

ASE is generated in the active fiber and travels forward and backward. The total ASE power is the sum of the forward and backward ASE powers in the *z*-direction in the erbium-doped fiber. ASE emission can be obtained from the following equations at a given wavelength:

$$\frac{dP^{+}_{ASE}}{dz} = \Gamma_s P^{+}_{ASE}(N_2\sigma_{21(se)} - N_1\sigma_{12(sa)}) + 2\Gamma_s\sigma_{21(se)}N_2 h\nu_s\Delta\nu - \alpha_s P^{+}_{ASE} \quad (5)$$

$$\frac{dP^{-}_{ASE}}{dz} = -\Gamma_s P^{-}_{ASE}(N_2\sigma_{21(se)} - N_1\sigma_{12(sa)}) - 2\Gamma_s\sigma_{21(se)}N_2 h\nu_s\Delta\nu + \alpha_s P^{-}_{ASE} \quad (6)$$

$$P_{ASE} = \Gamma_s\sigma_{21(sa)}N_2 P_0 \quad (7)$$

$$P_0(\lambda) = \frac{2hc^2}{\lambda^3} \quad (8)$$

Assuming Equation $\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0$, equations N_1 and N_2 are as follows:

$$N_1 = \frac{(1+W_{21}\tau_{21})N}{1+(W_{12}+W_{21})\tau_{21}+R_{12}\tau_{21}} \quad (9)$$

$$N_2 = \frac{(R_{12}\tau_{21}+W_{12}\tau_{21})N}{1+(W_{12}+W_{21})\tau_{21}+R_{12}\tau_{21}} \quad (10)$$

Finally, the following equations can be written for the pumping rate R_{12} and the throughput rate W_{ij} :

$$W_{12} = \frac{\Gamma_s\sigma_{12(sa)}}{h\nu_s A}(P_s + P^{+}_{ASE} + P^{-}_{ASE}) \quad (11)$$

$$W_{21} = \frac{\Gamma_s\sigma_{21(se)}}{h\nu_s A}(P_s + P^{+}_{ASE} + P^{-}_{ASE}) \quad (12)$$

$$R_{12} = \frac{\Gamma_p P_p\sigma_{12(pa)}}{h\nu_p A} \quad (13)$$

3. SIMULATION SETUPS (SİMÜLASYON DÜZENEKLERİ)

Figure 2 shows all doped fibers' single and double pass configurations. Table 1 shows the parameters used in the simulation for all doped fibers.

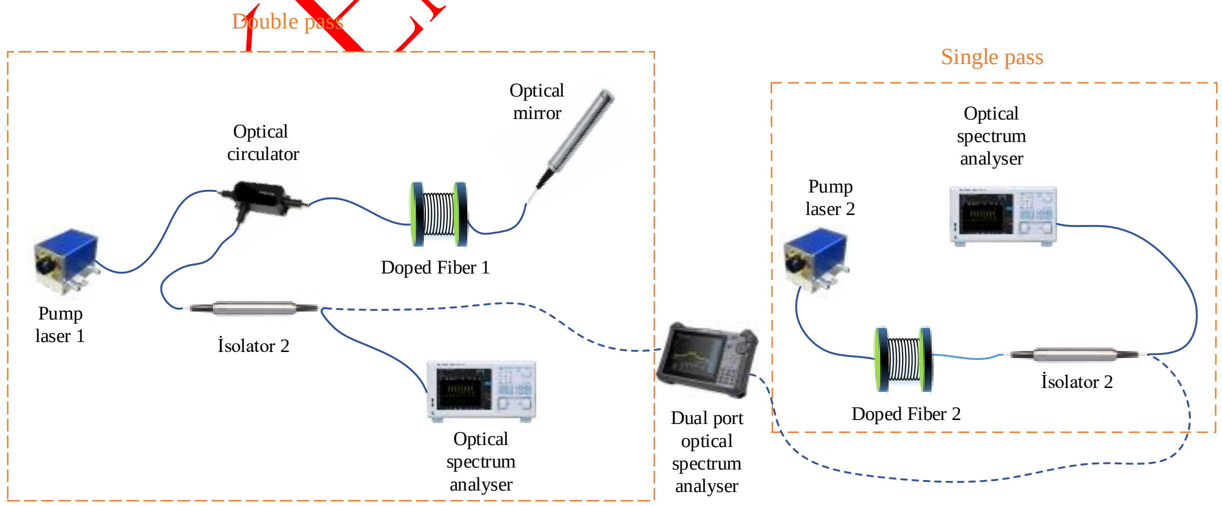

Figure 2. Single-pass and double-pass schemes (Tek ve çift geçişli düzenekler)

Table 1. Doped fiber parameters (Katkılı fiber parametreleri)

Parameters	EDFA	YDFA	EYDFA
Numerical aperture	0.24	0.2	0.15
Metastable lifetime (ms)	10	9.9	Er=10, Yb=1.5
Core radius (µm)	1.4	3.4	2
Ion density (m^-3)	2200	1000	Er= 5140, Yb= 6200
doping radius (µm)	1.3	3.4	2
Pump wave length (nm)	1480	960	1025
Pump power (mW)	400	800	1600
Doped fiber length (m)	4.3	6	16

3.1. EDFA Analysis (EDFA Analizi)

In this section, the results were obtained by placing Erbium-doped fiber (EDF) in the doped fiber blocks in Figure 2 and using the EDFA parameters in Table 1. Figure 2 shows the ASE comparison of two different setups fed from two pump sources in the EDFA simulation setup. The dual port optical analyzer makes the comparison, and the obtained result is shown in Figure 3. According to the results, the ASE value in the double-pass amplifier reached its highest value of -0.25 dBm at 1533 nm, and this value was obtained as -6.25 dBm at 1533 nm in the single-pass amplifier.

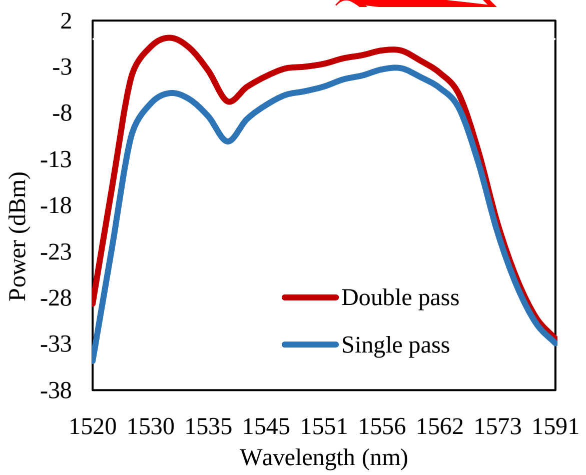

Figure 3. Comparison of ASE spectrums in EDFA double-pass and single-pass configurations (çift geçişli ve tek geçişli EDFA ASE spektrumlarının karşılaştırılması)

EDF absorption and emission values are shown in Figure 4. In the obtained graphs, as seen in Figure 2, the absorption and emission cross section reached their highest values at the wavelength where ASE has the highest value, and an increase is observed in these values at the point where ASE rises at 1558 nm.

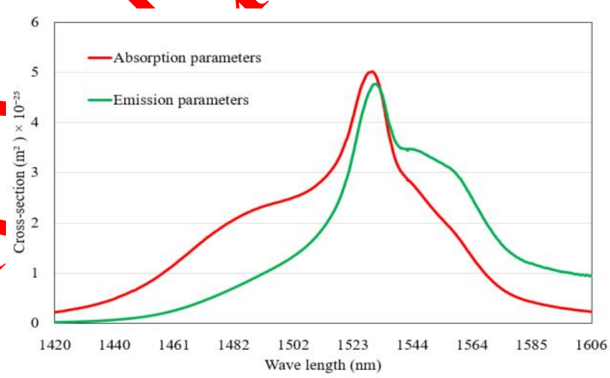

Figure 4. Erbium absorption and emission cross-section spectrums (Erbiyum soğurum ve yayılım kesit alanı spektrumları)

In this study, the EDF length was selected as 4.3 m. In Figure 5, the forward, backward ASE and N_1, N_2 change graphs were obtained according to the EDF length. N_2 had the highest and lowest values around the EDF length of 1.81 meters, and the reason for this is that the population inversion reached its maximum value. Therefore, this region's forward and backward ASE values reached minimum values. As the length increased, the population inversion value decreased with the increase of N_1 and the decrease of N_2 in the lengths after 3.62 meters, and thus, the forward ASE value also started to increase. The fact that N_1 and N_2 were equal at 3.65 meters shows that light's absorption and emission ratio is balanced.

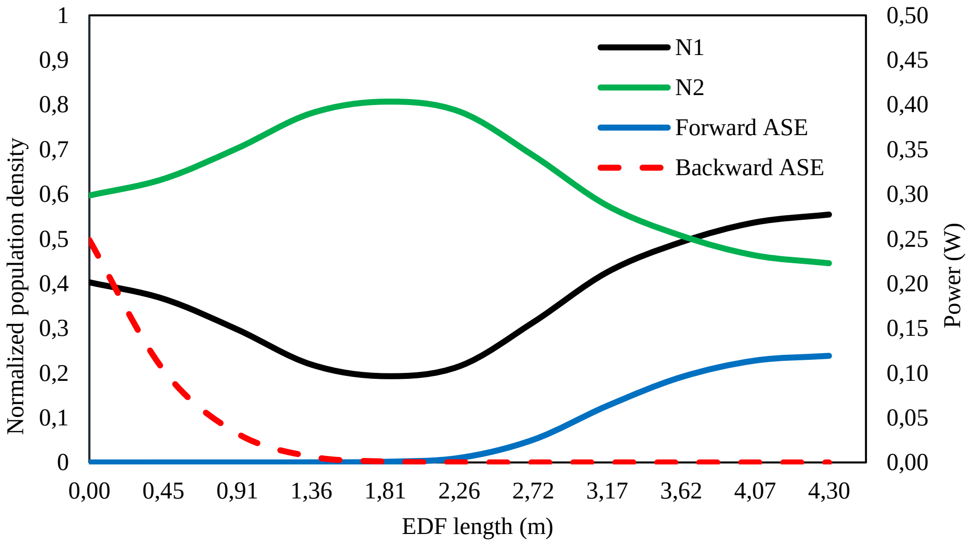

Figure 5. N_1, N_2, forward and backward ASE spectrums (İleri ve geri ASE, N_1 ve N_2 spektrumları)

3.2. YDFA Analysis (YDFA Analizi)

In the YDFA study, simulations and results were obtained for YDFA by taking the EDFA equations in Figure 1 as an example. The ASE graph is shown in Figure 6 using the same parameters in single and double-pass setups. The results were obtained using the YDFA parameter values in Table 1. According to the results, the ASE value increased to 9 dBm at the wavelength of 975.5 nm in the double pass simulation setup. This value was found to be -16.88 dBm for the single-pass system at the same wavelength. ASE values moved parallel to each other at wavelengths before 988 nm, and in the graphs after 988 nm, the two ASE intervals started to decrease and had almost equal values at 1100 nm.

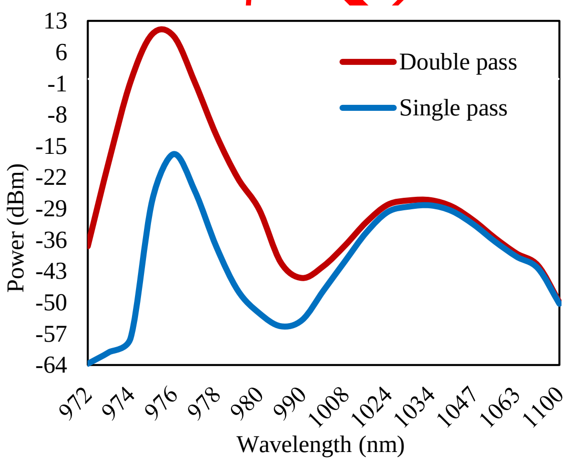

Figure 6. Comparison of ASE spectrums in YDFA double-pass and single-pass configurations (YDFA tek ve çift geçişli düzenekte ASE strumları)

Yb absorption and emission cross-section values were obtained graphically in this part of the study. The wavelength at which the emission has the highest value is the highest value reached by ASE. However, the wavelength at which the absorption value reaches the highest point is the wavelength at which ASE is the lowest.

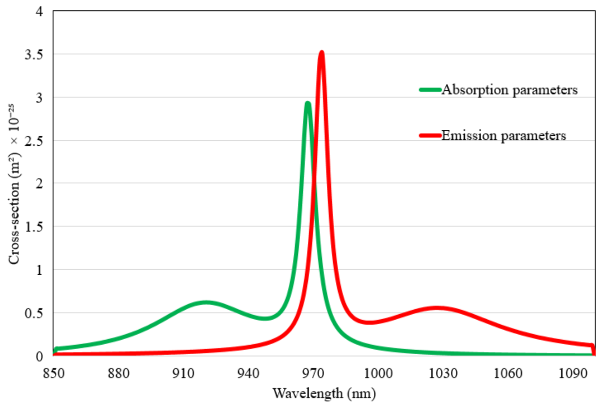

Figure 7. Yb absorption and emission cross-section spectrums (Yb soğurum ve yayılım kesit alan spektrumları)

Figure 8 shows Population N_1, Population N_2, forward ASE (F-ASE), and backward ASE (B-ASE). The number of electrons transferred from N_2 to N_1 reaches its highest value at the 1.3 m YDF length, and the forward ASE reaches its highest value with the number of electrons at the ground level reaching its highest value. At the length of 0.6 m, where N_2 has its highest value, the forward and backward ASE values become zero due to the high population inversion and in the region where stimulated emission is low.

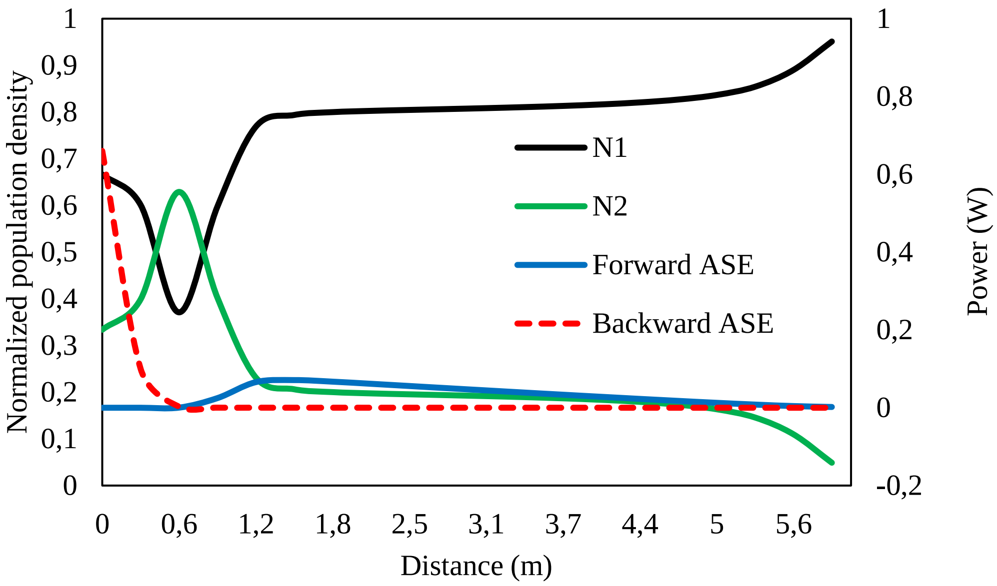

Figure 8. N_1, N_2, forward and backward spectrums in YDF (İleri ve geri ASE, N_1 ve N_2 spektrumları)

3.3. EYFDA Analysis (EYDFA Analizi)

For the EYDFA study, the equations obtained from the Erbium energy band level in Figure 1 were taken as an example, and the values of the parameters effective for ASE were obtained graphically using the EYDF parameters in Table 1.

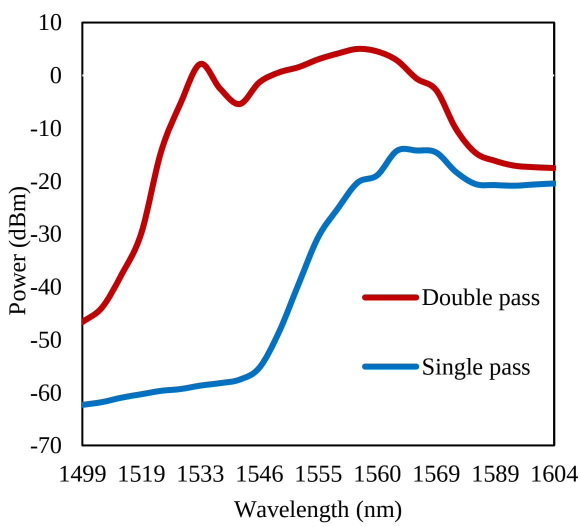

Figure 9. Comparison of ASE spectrums in EYDFA double-pass and single-pass configurations (Tek ve çift geçişli EYDFA düzeneğinin ASE spektrumları)

The ASE graphs of the double-pass and single-pass systems are shown in Figure 9. In the double-pass setup, the ASE value increased to 5 dBm at 1558 nm wavelength, and for the single-pass simulation environment, the highest ASE value increased to -14 dBm at 1565 nm. EYDFAs generally operate at a pump wavelength of 800-1100 nm; therefore, considering studies in the literature, a pump wavelength of 1025 nm was applied for EYDFA in this study. Since the applied pump wavelength is close to the YDFA operating pump wavelength, the Yb emission and absorption values are higher than Er in Figure 10. Other reasons for this are the transfer of the energy of the pump source from Yb to Er and the ion density of Yb being higher than that of Er.

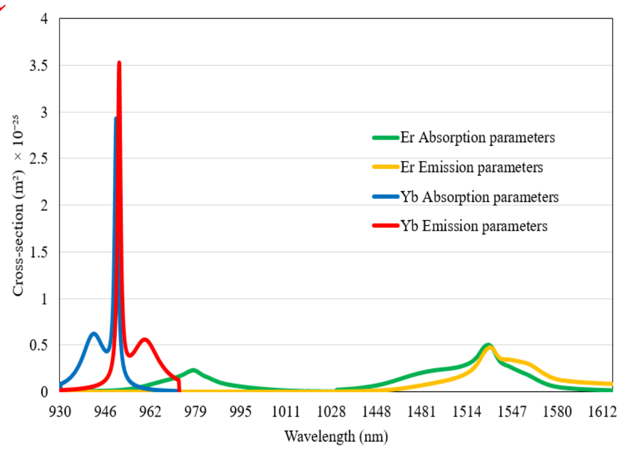

Figure 10. Yb and Er absorption and emission cross-sections spectrums (Yb, Er soğurum ve yayılım kesit alanı spektrumları)

Figure 11 shows the energy and total forward and backward ASE graphs in the EYDF band levels. Yb has an energy level of 2, and Er has an energy level of 4. Since the lifetimes of the electrons in the Er 3rd and 4th levels in the EYDF energy band level are very short, the energies of these levels are shown as zero in Figure 11, so as seen in the figure, the highest energy transfer (from 0 to 1W) is made for Yb at the N5 and N6 levels.

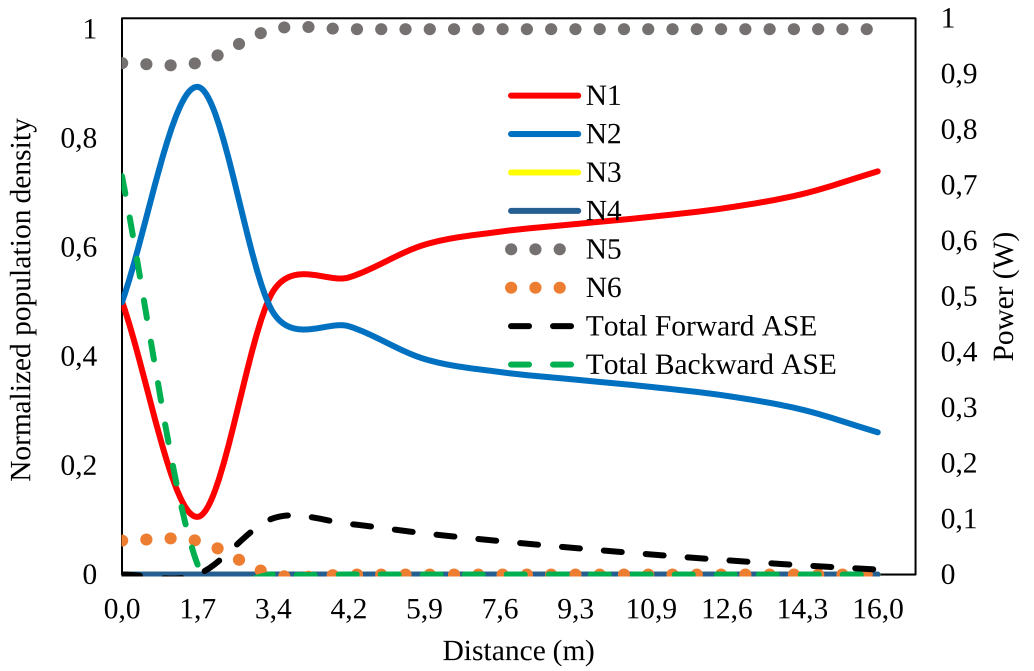

Figure 11. N1, N2, N3, N4, N5, N6, F-ASE and B-ASE according to EYDFA length (EYDFA uzunluğuna göre ileri ve geri ASE, N1, N2, N3, N4, N5 ve N6 spektrumları)

4. RESULTS AND CONCLUSIONS (BULGULAR VE SONUÇLAR)

In this study, Er, Yb, and Er-Yb doped optical amplifiers were examined and compared in single-pass and double-pass setups. The equations obtained from the Erbium energy band level (Figure 1) were taken as an example, and results were obtained for YDFA and EYDFA setups.

For the EDFA study, the highest ASE value in the double pass setup increased to 0 dBm at 1532 nm wavelength. At the wavelength where the emission value (Fig. 4) is highest, this value became -6 dBm in single pass at the same wavelength, and ASE values were obtained as 0 dBm and -3 dBm in double pass and single pass setups at 1558 nm wavelength, respectively.

In the YDFA setup, the highest ASE value was obtained at 975.3 nm in the region where the emission parameter is the highest, 11 dBm, while in the single pass setup, this value was obtained at 976 nm, -17 dBm. The highest ASE value obtained in the EYDFA simulation was 4.84 dBm at 1560 nm wavelength in the double pass setup and -14 dBm at 1568 nm in the single pass setup. In addition, the double pass setup increased the ASE spectrum to 2 dBm at 1533 nm.

As a result, the highest ASE value was obtained as 4.84 dBm in the C operating band at 1560 nm wavelength in the double pass EYDFA setup, and -14 dBm ASE value was obtained in the 1568 nm L band in the single pass setup with the same amplifier. As can be seen, in EDFA and YDFA amplifiers, the highest ASE values did not reach the L band, and with the combination of Er and Yb rare earth elements, the ASE peak value and the amplifier operating band also moved towards the L band.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Pouria PISHGAM*:** He conducted the simulations, analyzed the results, and performed the writing process.

Simülasyonları yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

***Murat YÜCEL*:** He conducted the simulations, analyzed the results, and performed the writing process.

Metodoloji, sonuçların kontrolü, yazımların incelenmesi ve düzeltilmesi işlemlerini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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