GAIN CHARACTERISTICS OF SHORT-LENGTH ERBIUM DOPED FIBER AMPLIFIERS AT EXTREME TEMPERATURES

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Erbium-doped fiber amplifiers are used for amplifying optical signals. In this type of optical amplifier, the core of a silica fiber is doped with Er^{3+} ions. Here, the effects of temperature on the gain parameters for short-length erbium-doped fiber amplifiers are simulated. Temperatures were selected over a wide range (−200 to +80°C) for different ion densities to simulate extreme conditions, such as the presence of liquid nitrogen. The maximum gain occurs at temperatures close to 0°C, and the Er^{3+} concentration also plays an important role.

Keywords: *fiber amplifier, temperature, ion density, gain, erbium.*

ХАРАКТЕРИСТИКИ ВОЛОКОННЫХ УСИЛИТЕЛЕЙ КОРОТКОЙ ДЛИНЫ НА ОСНОВЕ ЭРБИЯ ПРИ ЭКСТРЕМАЛЬНЫХ ТЕМПЕРАТУРАХ

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Волоконные усилители, легированные эрбием, используются для усиления оптических сигналов. В оптическом усилителе этого типа сердцевина кремнеземного волокна легирована ионами Er^{3+}. Смоделировано влияние температуры на параметры усиления легированных эрбием усилителей короткой длины. Для моделирования экстремальных условий, таких как присутствие жидкого азота, выбраны температуры в широком диапазоне (от –200 до +80° С) при различных плотностях ионов. Максимальное усиление наблюдается при температурах, близких к 0 °С. Отмечена важная роль концентрации Er^{3+}.

Ключевые слова: *волоконный усилитель, температура, плотность ионов, коэффициент усиления, эрбий.*

Introduction. The use of erbium-doped fiber amplifiers (EDFAs) has become a necessity because of the increasing demand for long-distance signal transmission, which can result in defective signals [1]. The length of the fiber amplifier is one of the most important factors, and the optimum length is related to other parameters such as the amount of pumping for saturated EDFAs [2]. The gain coefficient, shown below, is a function of ion distributions and optical modes, where i_k is the normalized optical intensity, and n_t is local erbium ion density [3, 4]:

$$g_k(\lambda_k, z) = \sigma_e(\lambda_k) \int_0^{2\pi} \int_0^{\infty} i_k(r, \varphi) n_t(r, \varphi, z) r dr d\varphi .$$

Operation at 980 nm is less affected by temperature than that at 1480 nm. Moreover, for the same setup, 1480 nm operation is affected more by the strength of the signal in the standard three-level system of Giles and also by Rayleigh backscattering [5]. The effects of temperature on optical amplification clearly affect the behavior of EDFA properties [3, 6].

Previously, temperature-dependent gain and power characteristics of EDFAs were shown in terms of temperature-dependent signal emission and absorption cross-sections and their impact on L-band output power [7]. Additionally, a study on the effect of pump laser wavelength on the temperature dependence revealed that the temperature-dependent gain variation of EDFA is lower for a 980-nm pump wavelength [8]. Other reports examined variations in EDFA gain flattening [9]. One report provided a theoretical approach to the propagation equation for EDFAs pumped at 1480 nm [10], and another discussed a numerical approach to the temperature dependence [11]. The lowest temperature reported in these studies was −40ºC, while the highest temperature was 80ºC. Thus, there have been no reported studies that covered a wider temperature range including extremely cold temperatures, such as −200ºC, with different erbium ion concentrations. These very low temperatures include cryogenic systems, with applications in medicine, energy, chemistry, experimental applied physics, quantum computing, and cryogenic computing [12, 13]. Recent optic fiber studies at cryogenic temperatures include assemblies for spaceflight environments [14], the investigation of five different fiber-optic sensors [15], and the validation of a novel fiber-optic strain gauge [16]. Therefore, the simulation and characterization of an EDFA over a wide temperature range is of interest and may be useful for the development of technological applications.

The temperature effect on gain is a primary factor in the design specifications of systems using EDFA. Therefore, the temperature should be investigated to determine the optimum value for the EDFA configuration, in addition to studying the roles of other important system factors [3]. The aim here is to determine the optimum gain in the C-band spectral range as a function of temperature for a given fiber length.

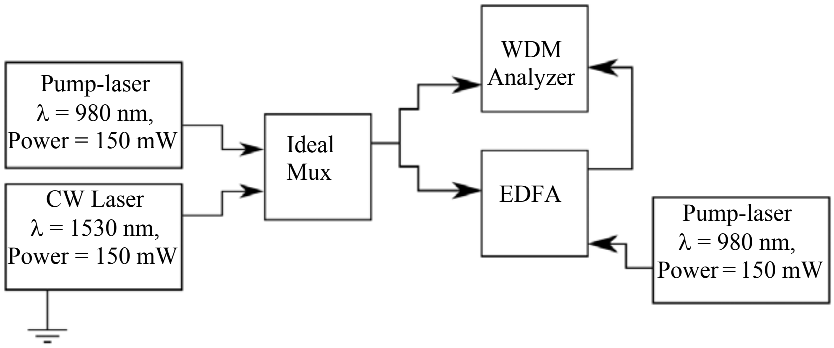

Fig. 1. Erbium-doped fiber amplifier setup for the simulations.

Methods. Optiwave software (OptiSystem5.0, evaluation version, Ottawa, Canada) was used to simulate the optical communication system. The initial optical fiber length of 1 m was increased in 2 m increments, the temperature was varied from −200 up to +80°C, the pump wavelength was 980 nm with a power of 150 mW, and three different ion densities (5×10^{24}, 7.5×10^{24}, and 1×10^{25} m^{-3}) were used. The numerical aperture was 0.3. A schematic of the setup used in the simulations is shown in Fig. 1, which used a standard unmodified single-mode fiber.

Results and discussion. For fiber lengths up to 7 m, the gain increases with temperature up to 80°C. Above 7 m, the gain decreases with temperature. The central point where the gain starts to decrease for a 7-m fiber length is −80°C. The maximum gain value is 42.95 dB for a 3-m fiber at +80°C.

To determine which length is the best for a specific temperature, it is very important to get the optimum gain in the amplification process. For 1-m and 3-m lengths, the linear gain increases with the temperature, as shown in Fig. 2. Even though the gain was increasing for the 9-m and 11-m lengths, the optimum length for a more stable gain and signal is 5 m, because the gain and signal will not be affected by temperature changes [3]. The effects of temperature are minimal for the 5-m length fibers compared with the other variants. Figure 2a shows the EDFA gain profile for an ion density of 5×10^{24} m^{-3}. Shorter lengths (1–5 m) exhibit an approximately linear increase over the entire temperature range. For formulations with a 7.5×10^{24} m^{-3} ion density, similar increases are observed for the shorter lengths; however, the gain values decrease above 0ºC for fibers longer than 7 m (Fig. 2b). This reversed behavior is clearly visible for fibers having an ion density of 1×10^{25} m^{-3} (Fig. 2c); at a length of 11 m, the gain significantly decreases to ~10 dB with increasing temperature. This decrease can be explained by the gain saturation mode, where the boost in high signal power will decrease the gain and the EDFA cannot maintain an additional arbitrary signal.

The most common behavior for all the formulations is that the gain remains constant at around 43 dB for very low temperatures (<100ºC). Additionally, by increasing the ion density, the necessary EDFA length for the most stable gain decreases (see 11, 7, and 5 m, respectively, in Fig. 2).

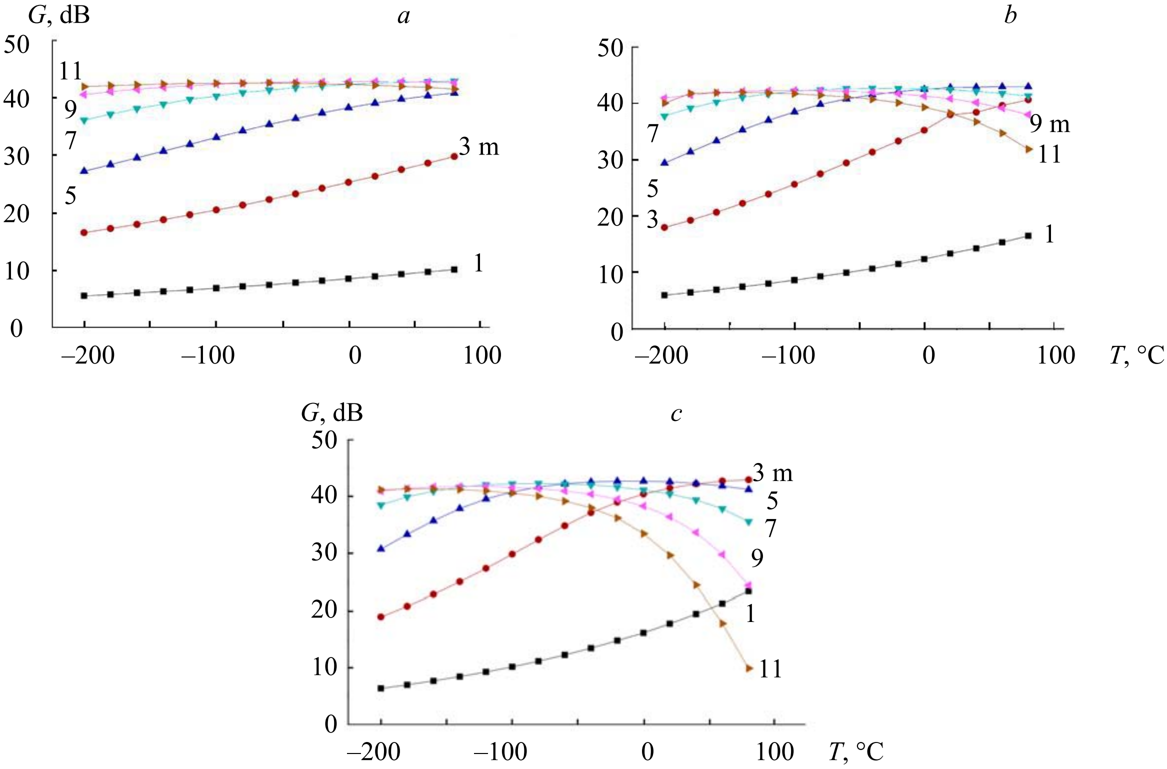

Fig. 2. Effect of temperature on the amplifier gain for different fiber lengths.
The ion density was 5×10^{24} (a), 7.5×10^{24} (b), and 1×10^{25} m^{-3} (c).

Conclusions. The effect of temperature on short-length EDFAs was simulated. Lengths of 11, 7, and 5 m had the most stable gains for 5×10^{24}, 7.5×10^{24}, and 1×10^{25} m^{-3} ion densities, respectively. In upcoming studies, the short-length EDFA gain will be analyzed experimentally for use in extreme-temperature conditions.

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