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Jose Alfredo Alvarez-Chavez, Rafael Sanchez-Lara, Jose L. Vazquez-Avila, Daniel Enrique Ceballos-Herrera, Herman L. Offerhaus, "Thermal effects on tapered holmium-doped fiber amplifiers," *Opt. Eng.* **59**(3), 036106 (2020), doi: 10.1117/1.OE.59.3.036106

Thermal effects on tapered holmium-doped fiber amplifiers

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Abstract. The temperature response of a tapered holmium-doped fiber amplifier and its impact in the performance of fiber lasers and temperature fiber sensors has numerically been analyzed. Different pump schemes and different longitudinal shapes of the tapered-doped fiber were investigated, and it was found that a parabolic shape of the tapered fiber amplifier in a co-propagating pump scheme shows the highest sensitivity to temperature changes. In particular, the temperature sensitivity of the amplified signal was $2.5 \times 10^{-4}^{\circ}\text{C}$ for 1 W of pump power and 1 m of doped fiber length. In addition, this sensitivity can be increased up to 10 times for fiber lengths shorter than 1 m and pump powers lower than 300 mW. Our results can be used to describe the temperature response of tapered fiber amplifiers in the mid-infrared spectral region and contribute with new information for the development of fiber lasers and fiber temperature sensors. © 2020 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.59.3.036106](https://doi.org/10.1117/1.OE.59.3.036106)]

Keywords: holmium-doped fibers; tapers; amplifiers; thermal effects.

Paper 191638 received Nov. 25, 2019; accepted for publication Feb. 19, 2020; published online Mar. 10, 2020.

1 Introduction

Recently, holmium-doped fiber lasers operating in the $2.1\text{-}\mu\text{m}$ spectral region have become a key for many applications. Among them, the development of high-power lasers for LIDAR (due to its excellent atmospheric transmission), gas sensing, medicine, material processing, and nonlinear optical conversion in the mid-infrared.^{1–5} In this context, many efforts have been made to improve the performance of holmium-doped fiber lasers. One interesting strategy is using a tapered-doped fiber to increase the absorption of the pump along the doped core, which consequently helps improve the power conversion between the pump and signal. This approach has extensively been used to develop high-power Yb-doped fiber lasers^{6–9} and can also be used to increase the efficiency of holmium-doped fiber lasers. However, special attention should be paid to thermal effects in tapered holmium-doped fibers since the temperature dependence of the pump and signal cross sections of holmium ions modifies the modal behavior of the propagating radiation in the tapered waveguide, which in time produces variations in the power conversion at the end of the doped-fiber. This fact has already been demonstrated in Yb- and Tm-doped fiber amplifiers.^{10–14} Thus it is reasonable to expect the similar effects in tapered holmium-doped fibers. However, this issue has not been investigated in detail. For this reason, in this work, a numerical analysis of thermal effects in tapered holmium-doped fiber amplifiers is reported in order to study the temperature sensitivity of the power conversion between the pump and signal, using tapered fibers with different longitudinal shapes. Additionally, a discussion on how these results can be applied in the development and optimization of holmium-doped fiber lasers and temperature fiber sensors is included.

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2 Numerical Experiment, Results, and Discussion

The analysis starts by considering first a tapered section that is formed by a single-mode step index fiber surrounded by air. Therefore, only the mode field expression of the fundamental core mode within the tapered fiber is considered. The mode field expression is an important parameter in doped fiber amplifiers because it determines the core mode fraction of the pump and signal, which affects the power conversion in the doped core. In this study, Gaussian shapes for the pump and signal fundamental core modes were considered. Thus the transverse intensity pattern using a Gaussian envelope approximation given by Ref. 15 can be written as

$$f_{p,s}(r) = \frac{1}{\pi\Omega^2} e^{-r^2/\Omega^2}, \quad (1)$$

where subscripts p and s refer to pump and signal radiations, and Ω is determined by the refractive indices and radius of the core and cladding, respectively. The multiplying factor in Eq. (1) is chosen to normalize $f(r)$ as follows: $2\pi \int f_{p,s}(r) dr = 1$.

For a step index fiber, Ω is approximately given by the following expression:

$$\Omega = aJ_0(U) \frac{V K_1(W)}{U K_0(W)}, \quad (2)$$

where a is the core radius, $U = a\sqrt{k^2 n_1^2 - \beta^2}$, $W = a\sqrt{\beta^2 - k^2 n_2^2}$, $V = ka\sqrt{n_1^2 - n_2^2}$, $k = 2\pi/\lambda$, n_1 and n_2 are the refractive indices of the core and cladding, respectively, and β is the propagation constant of the pump or signal mode. For a given V , the value of W can be obtained using the Rudolph–Neumann approximation: $W = 1.1428V - 0.996$ valid only for single-mode step index fibers.¹⁵ In this way, after choosing to the pump and signal wavelengths, one can obtain the respective values for U , W , and V using the numerical aperture (NA) of the fiber ($NA = \sqrt{n_1^2 - n_2^2}$), and subsequently the Ω parameter. It is worth mentioning that the core mode field expression given in Eq. (1) can be slightly modified due to variations of the core- and cladding-refractive index caused by temperature. However, these mode field variations are negligible in a temperature range from 20°C to 120°C as it was reported Ref. 14.

In order to analyze the thermal effects on the doped-fiber amplifier, the changes of the absorption and emission cross section of the holmium ions with respect to temperature were considered. Previous works in untapered fibers have reported changes in population of the energy levels in holmium-doped glasses.^{16,17} These changes cause modifications of the absorption and emission cross sections for the signal and pump radiations. These effects may vary for each individual doped fiber due to the different glass compositions, concentration of holmium dopants and co-dopants, and the degree of structural disorder on the glass network used in different fibers. Without loss of generality, the absorption and emission cross sections change with temperature given in Ref. 16, which are representative of several holmium-doped fibers are used. These changes are expressed in the following equations:

$$\sigma_{\text{abs}}^{1940}(T) = 2.21 \times 10^{-24} - 6.49 \times 10^{-27}T, \quad (3)$$

$$\sigma_{\text{em}}^{1940}(T) = 1.59 \times 10^{-24} - 4.34 \times 10^{-27}T, \quad (4)$$

$$\sigma_{\text{abs}}^{2090}(T) = 9.09 \times 10^{-26} + 1.01 \times 10^{-27}T, \quad (5)$$

$$\sigma_{\text{em}}^{2090}(T) = 3.54 \times 10^{-24} - 1.04 \times 10^{-26}T, \quad (6)$$

where $\sigma_{\text{abs}}^{2090}$ and $\sigma_{\text{em}}^{2090}$ are the absorption and emission cross sections for the signal wavelength and, $\sigma_{\text{abs}}^{1940}$ and $\sigma_{\text{em}}^{1940}$ are the absorption and emission cross sections for the pump wavelength, respectively.

In order to model a temperature-dependent tapered holmium-doped fiber amplifier, the following coupled equations are analyzed:

$$\frac{dI_p(r, z)}{dz} = [\sigma_{em}^p(T) \times n_{-2}(T) - \sigma_{abs}^p(T) \times n_{-1}(T)] N_{tot} I_p(r, z), \quad (7)$$

$$\frac{dI_s(r, z)}{dz} = [\sigma_{em}^s(T) \times n_{-2}(T) - \sigma_{abs}^s(T) \times n_{-1}(T)] N_{tot} I_s(r, z), \quad (8)$$

where $I_p(r, z)$ and $I_s(r, z)$ are the pump and signal intensities, N_{tot} is the total holmium population, σ_{abs}^p , σ_{em}^p , σ_{abs}^s , and σ_{em}^s are the temperature-dependent absorption and emission cross sections of the pump and signal at 1940 and 2090 nm, respectively, and $n_{-1}(T)$, $n_{-2}(T)$ are the temperature-dependent upper and lower-state population levels of holmium, which are given at a steady-state by the following equations:

$$n_{-2} = \frac{R_{abs} + W_{abs}}{R_{abs} + R_{em} + W_{abs} + W_{em} + A_{esp}}, \quad (9)$$

$$n_{-1} = 1 - n_{-2}, \quad (10)$$

where $R_{abs} = \sigma_{abs}^p I_p h\nu_p$, $R_{em} = \sigma_{em}^p I_p h\nu_p$, $W_{abs} = \sigma_{abs}^s I_s h\nu_s$, and $W_{em} = \sigma_{em}^s I_s h\nu_s$.

In these equations, the amplified spontaneous emission generation is not considered and only effects of the taper and modifications of the cross sections by temperature are investigated.

To consider the taper effects and the overlap of the pump and signal fundamental mode with the active core, the following expression can be used

$$I_{p,s}(r, z) = P_{p,s}(z) f_{p,s}(r), \quad (11)$$

where subscripts p and s refer to pump and signal radiations, $P_{p,s}(z)$ are the z -dependent powers at the pump and signal wavelengths, and $f(r)$ is given by Eq. (1). It is clear at this point that the effect of a taper in parameter Ω defined in Eq. (2) directly modifies the evolution of pump and signal intensities described in Eqs. (7) and (8).

If the pump power at any value of z is considered, we have

$$P_{p,s}(z) = \int_0^\infty \int_0^{2\pi} I(r, z_{p,s}) r dr d\varphi = 2\pi \int_0^\infty I_{p,s}(r, z) r dr. \quad (12)$$

Then

$$\frac{dP_{p,s}(z)}{dz} = 2\pi \int_0^\infty \frac{dI_{p,s}(r, z)}{dz} r dr. \quad (13)$$

Using Eqs. (11) and (13), Eqs. (7) and (8) can be rewritten as follows:

$$\frac{dP_p(z)}{dz} = 2\pi \int_0^{a(z)} [\sigma_{em}^p(T) \times n_{-2}(T) - \sigma_{abs}^p(T) \times n_{-1}(T)] N_{tot} P_p(z) f_p(r) r dr, \quad (14)$$

$$\frac{dP_s(z)}{dz} = 2\pi \int_0^{a(z)} [\sigma_{em}^s(T) \times n_{-2}(T) - \sigma_{abs}^s(T) \times n_{-1}(T)] N_{tot} P_s(z) f_s(r) r dr. \quad (15)$$

On these equations, it has been assumed that the fiber is doped with a uniform holmium-concentration up to the core radius “ a ,” which depends on z . It is of note that the populations $n_{-1}(T)$ and $n_{-2}(T)$ depend on $f_{p,s}(r)$ due to their relation with I_p and I_s intensities. Once the temperature-dependent coupled equations are defined, we proceed to model a tapered holmium-doped fiber amplifier with different tapered core shapes, as shown in Fig. 1.

The geometrical profiles of the schemes named forward taper and backward taper in Fig. 1 are expressed by Eqs. (16) and (17) in the following way:

$$r(z) = \left(\frac{1}{c}\right)(-D - Bz - z^2), \quad (16)$$

Fig. 1 Numerical setup of tapered holmium-doped amplifiers with different tapered core shapes ($i = 1, 2$, and 3). The simulation was performed using pump and signal in a co-propagating mode in the following schemes: (a) forward taper and (b) backward taper.

Table 1 Taper equation coefficients.

Suffix (i)	B	C	D
1	-2.6054×10^{-6}	1.8×10^7	-36
2	-1.6121×10^3	-9.6546×10^9	1.9309×10^4
3	-5.9889	-1.7933×10^7	35.8662

$$r(z) = \left(\frac{1}{c}\right)[-D - B(L - z) - (L - z)^2], \quad (17)$$

where $L = 1$ m corresponds to the fiber length. The parabolic equations ($i = 1, 2, 3$) for each taper schemes 1 and 2 are defined by the coefficients B , C , D shown in Table 1.

First, the power conversion along the fiber between the pump and signal radiations for the different taper schemes as described in Fig. 1 is analyzed. In this first numerical experiment, the $NA = 0.18$ is considered constant along the taper and the temperature is changed from 290 to 390 K. For both schemes shown in Fig. 1, the co-propagating pump and signal power (P_p and P_s) were set at 1 W and 10 mW, respectively. The corresponding results of the signal conversion for three different temperatures are shown in Fig. 2 for each longitudinal tapered core shape.

In Fig. 2, the power conversion between the pump and signal radiations along the tapered-doped fiber using both taper schemes (forward taper and backward taper), respectively, can be observed. In particular, the crossing point (where the power conversion is maximum) is located at different lengths for the two taper schemes. The cross-point length in incises (a), (b), and (c), which correspond to the forward taper, always occurs at a shorter fiber length (around 0.01 m) compared to that obtained for the backward taper scheme (which occurs between 0.1 and 0.4 m approximately). This difference on the cross-point length of approximately one order of magnitude between the taper schemes is only observed in tapered holmium-doped fiber amplifiers. It can be noted that for tapered Yb-doped fiber amplifiers, the differences of the cross-point length observed in such taper schemes (forward taper and backward taper) are negligible.¹³

In Fig. 2, for the backward taper scheme, it can also be observed that the cross-point length in incises (d), (e), and (f) highly depends on the tapered core profile and shifts from 0.1 to 0.4 m according to the suffix $i = 1, 2, 3$, respectively. On the other hand, for the forward taper scheme, the cross-point length in incises (a), (b), and (c) stays around 0.01 m for different suffixes $i = 1, 2, 3$. The above observations suggest that the holmium-doped fiber amplifier can be implemented for shorter tapered fiber lengths using the forward taper scheme and shows a more stable power

Fig. 2 Evolution of the pump and signal radiations (P_p and P_s) at three different temperatures: incisives correspond to the scheme named (a)–(c) forward taper and (d)–(f) backward taper. In all cases, the initial pump and signal powers were set at 1 W and 10 mW.

conversion for different tapered core shapes. In Fig. 2, one can also observe how the temperature affects the power conversion between the pump and signal radiations. In particular, the crossing-point length shifts to longer distances as temperature increases. This temperature dependence is very similar for both taper schemes. Also for all tapered fiber configurations, it can be observed that the shift of the cross-point length, when the fiber temperature is increased from 290 to 360 K, is higher than that obtained for the case when the temperature increases from 360 to 390 K. It suggests a possible saturation of the temperature response in the tapered holmium-doped fiber amplifier for temperatures higher than 360 K.

To visualize the temperature effect on the performance of the tapered-doped-fiber amplifier, we proceed to analyze the amplified signal power at the end of the tapered fiber at 290 K with respect to the signal generated at different temperatures T , using the following normalized expression: $\Delta = [P_s(290 \text{ K}) - P_s(T)]/P_s(290 \text{ K})$. This equation has been calculated for each tapered core shape considered in this work with a fiber length = 1 m, a pump power = 1 W, and a signal power = 10 mW, respectively. The results are shown in Fig. 3.

According to Fig. 3, for both schemes named forward taper (in black color) and backward taper (in blue color), all tapered-doped-fiber amplifiers show a constant increment of Δ with respect to temperature from 290 to 350 K. In this temperature range, all curves follow a linear profile and their slopes indicate the sensitivity of the normalized amplified signal (Δ) with respect to temperature (T) for different tapered holmium-doped fiber amplifiers. In this sense, from Fig. 3, a curve with a maximum positive slope ($+2.5 \times 10^{-4} \text{ K}$) which corresponds to the case of using the forward taper scheme and using a parabolic taper shape given by the suffix $i = 1$ (black line) can be observed. On the other hand, in Fig. 3, it can be observed that all curves reach a saturation of Δ at around 360 K. If one compares the results on temperature sensitivities

Fig. 3 Normalized amplified signal for different temperatures at the end of the tapered fiber with $L = 1$ m.

with respect to those obtained using tapered Yb-doped fibers (Fig. 3 of Ref. 14), it is observed that these are very similar; however, for the tapered holmium-doped fibers, saturation in the curves is present.

The curves shown in Fig. 3 also represent a design map that allows choosing the adequate taper shape and its corresponding taper length to increase or reduce the temperature sensitivity around a specific temperature value. For holmium-doped fiber lasers, it is convenient to have a reduced temperature sensitivity to reach a more stable operation, in this case, the use of a backward taper scheme with a parabolic profile ($i = 3$) in the temperature range between 350 to 380 K is recommended. On the other hand, for temperature fiber sensors, it is desirable to obtain a high-temperature response of the holmium-doped fiber amplifier. Therefore, the use of a forward taper scheme with a parabolic profile ($i = 1$) in a temperature range between 290 and 350 K is recommended. In addition, the temperature response shown in Fig. 3 for a fiber length of 1 m can be improved for shorter fiber lengths. According to Fig. 2, the highest changes of the amplified signal with respect to temperature occurs around 0.01 m for the “forward taper” scheme, and around 0.1 m for the “backward taper” scheme, respectively.

Figure 4 shows the temperature response at different pump powers for the two tapered core shapes analyzed in this work, where temperatures of 300 and 390 K are used. The signal is calculated at the end of the tapered fiber (1 m) using both taper schemes shown in Fig. 1. According to Fig. 4, the temperature sensitivity of the tapered-doped fiber amplifier grows for low values of the initial pump power. This behavior is similar for different tapered fiber lengths in both taper schemes (forward taper and backward taper). This is an important result to consider for the design of fiber lasers and temperature fiber sensors.

According to Fig. 4, the temperature sensitivity of the signal radiation for both “forward taper” and “backward taper” schemes can also be increased up to 10 times for pump powers lower than 300 mW in comparison to using pump powers of 1 W, respectively. In particular, this

Fig. 4 Temperature behavior of the generated signal for temperatures $T = 300$ and 390 K at different pump powers (0.2 to 1 W), (a) forward taper, $i = 1$ and 3 and (b) backward taper, $i = 1$ and 3.

increment on sensitivity highly depends of the taper shape used. Additionally, it is worth mentioning that the tapered fiber length also determines the dimensions of the temperature-sensing element due to the consideration that the whole optical doped-fiber is subject to changes in temperature. In this context, the taper length required to obtain the power conversion in holmium-doped fiber amplifiers is lower than these required in other rare-Earth-doped fiber amplifiers.^{13,14} Then holmium-doped fiber amplifiers can offer an opportunity to develop more compact temperature fiber sensors. In this sense, further analysis needs to be performed to optimize the temperature sensitivity using different taper ratios and the longitudinal shape of the tapered holmium-doped-fiber by employing more reduced fiber lengths.

3 Conclusion

Numerical analysis of the temperature effects in tapered holmium-doped fiber amplifiers in co-propagation mode has been reported. It has been found that the tapering shape and the pump power at the input amplifier significantly modify its temperature sensitivity. In particular, the temperature sensitivity is slightly higher as the core radius is increased in the propagation direction (“forward taper” scheme). On the other hand, a higher temperature sensitivity can be achieved if we consider lower tapered-fiber lengths, because at the cross point where it occurs, the power conversion is more sensitive to temperature and it happens at taper lengths lower than 1 m. In this sense, tapered holmium-doped fiber amplifiers can be used to develop more compact temperature fiber sensors in comparison to other tapered fiber amplifiers doped with other rare-earths. On the other hand, the temperature sensitivity can also be incremented up to 10 times if lower pump powers at the amplifier input are employed. Then for temperature sensing applications, it is desirable to work using tapered-doped fiber amplifiers in low pump power regimes. Electrical temperature sensing using bimetals requires leads that cause losses and parasitic resistance over large distance. Fiber optic temperature sensing can be done over much larger distances due to the relatively low losses. Most fiber-based sensing is currently done mostly using distributed temperature sensing (DTS) or using fiber Bragg gratings (FBGs). Compared to DTS, the holmium taper has the advantage that it is localized so that temperature can be monitored at the end of a (long) fiber, e.g., in an underground temperature storage or in a reaction vessel. Compared to FBG sensing (which is also localized), the holmium fiber has the advantage of being dependent purely on temperature, not on strain (a compounding factor in FBG sensing). The further advantage that these lasers can be sufficiently powerful to transmit over long distance but operate at a wavelength that is eye safe makes them an interesting candidate for sensing. Finally, results from this work provide valuable information for the development of holmium-doped fiber lasers and temperature fiber laser sensors.

Acknowledgments

The authors are grateful to UNACAR, UNAM, CIITEC-IPN, and CONACYT in Mexico, and the Optical Sciences group at the University of Twente in The Netherlands.

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