



Research Article

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A high-gain cladded waveguide amplifier on erbium doped thin-film lithium niobate fabricated using photolithography assisted chemo-mechanical etching

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Abstract: Erbium doped integrated waveguide amplifier and laser prevail in power consumption, footprint, stability and scalability over the counterparts in bulk materials, underpinning the lightwave communication and large-scale

sensing. Subject to the highly confined mode in the micro-to-nanoscale and moderate propagation loss, gain and power scaling in such integrated devices prove to be more challenging compared to their bulk counterparts. In this work, a thin cladding layer of tantalum pentoxide (Ta_2O_5) is employed in the erbium doped lithium niobate (LN) waveguide amplifier fabricated on the thin film lithium niobate on insulator (LNOI) wafer by the photolithography assisted chemo-mechanical etching (PLACE) technique. Above 20 dB small signal internal net gain is achieved at the signal wavelength around 1532 nm in the 10 cm long LNOI amplifier pumped by the diode laser at ~ 980 nm. Experimental characterizations reveal the advantage of Ta_2O_5 cladding in higher optical gain compared with the air-clad amplifier, which is further explained by the theoretical modeling of the LNOI amplifier including the guided mode structures and the steady-state response of erbium ions.

Keywords: integrated waveguide amplifier; lithium niobate nanophotonics; photolithography assisted chemo-mechanical etching.

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Erbium doped integrated waveguide laser and amplifier, the essential analogs of prevalent erbium doped fiber laser and amplifier, have been intensively investigated under an abundance of material platforms in the recent decades [1–4]. Photonic integration brings various advantages including small footprint, low power consumption and high stability and scalability to the desired waveguide laser and amplifier, though stringent limitations on the attainable gain/power arise due to the highly confined optical mode and moderate propagation loss. In contrary to erbium doped optical fibers which favor effective absorption lengths of tens of meters due to their extremely low propagation loss [5, 6], integrated waveguides feature much higher loss and inhomogeneity limiting the available gain length from few-millimeters to tens of centimeters. As a result, the erbium doping concentration in integrated

waveguide amplifiers ($>10^{20}/\text{cm}^3$) is compelled to be much higher than that in fiber amplifiers ($10^{18}\text{--}10^{19}/\text{cm}^3$) to maintain comparable optical gain [7, 8]. High concentration doping instead incurs adverse effects including migration-accelerated energy transfer upconversion (ETU) among excited ions, fast quenching by static ETU among excited ions or clusters, and excited state trapping by host material defects [9, 10]. Such effects degrade the establishment of high population-inversion gain, putting an inherent limit on the attainable gain and engendering delicate optimizations on the doping concentration for specific waveguide configurations.

Integrated lithium niobate (LN) nanophotonics have been broadly investigated in recent years, benefited from the excellent electro-optic, acousto-optic and nonlinear optical properties of LN and the maturing development of high-quality lithium niobate on insulator (LNOI) thin film wafer and its photonic integration technique [11–14]. Recent demonstration of erbium doped LNOI laser and amplifier has stimulated great interests in developing active LNOI components and passive/active hybrid integration methods [15–24]. The erbium doped LNOI waveguide amplifier holds great promise among such quest due to its broad applicability in telecommunication and sensing. Various groups have reported LNOI waveguide amplifiers with diverse footprints and gain performance [20–24], and the maximum small signal internal net gain of ~ 18 dB is achieved in a 3.6 cm long LNOI amplifier [22].

In this work, an efficient LNOI waveguide amplifier with high erbium doping concentration ($\sim 1.9 \times 10^{20}/\text{cm}^3$) is fabricated, featuring above 20 dB small signal internal net gain at the signal wavelength of ~ 1532 nm pumped by ~ 980 nm laser diode. Experimental characterizations of the LNOI waveguide amplifiers with/without a thin cladding layer of tantalum pentoxide (Ta_2O_5) demonstrate the superior gain performance of the Ta_2O_5 -clad amplifier compared to the air-clad amplifier. Theoretical modeling based on the submicron-scale optical mode distributions and the steady-state response of erbium ions reveal the role of Ta_2O_5 cladding in mitigating the counteracting effect of quenched active ions for high inversion gain. This work pinpoints the significant role of optical mode control in the active LNOI nanophotonic platform for high gain/power operation. Further power scaling of LNOI amplifier by cladding pumping in analogy to the double-cladding fibers is also discussed.

The 600 nm thick Er^{3+} -doped Z-cut LN thin film is ion-sliced from the bulk Er^{3+} -doped LN crystal by the ‘smart-cut’ technique [11], which resides atop of a 2 μm thick silica layer for optical isolation with the underneath 0.5 mm-thick

silicon substrate. The LNOI waveguide is fabricated using the photolithography assisted chemo-mechanical etching (PLACE) technique [25, 26], and the fabrication details are similar to our previous works and also described in the supplemental materials. The schematic for the waveguide cross section is shown in Figure 1(a), and the LN core features a top width of 2 μm and a bottom width of 6 μm which can be inferred from the top-view reflective microscope image of the fabricated LNOI waveguide shown in Figure 1(b). A thin layer of Ta_2O_5 with ~ 1 μm thickness is further deposited on top of the LN core. The waveguide input and output facets are prepared by focused ion beam (FIB) milling, with the scanning electron microscope (SEM) image shown in Figure 1(c). The tilt angle of SEM image is about 52° . The fundamental TE-mode profiles at the pump wavelength (976 nm) and the signal wavelength (1532 nm) employed in the amplifier gain measurement are calculated by finite element method and depicted in Figure 1(d) and (e), for the air-clad and Ta_2O_5 -clad LNOI waveguides, respectively. Clearly, due to the reduced refractive index contrast between LN (refractive index $n_o \sim 2.212$, $n_e \sim 2.138$) and Ta_2O_5 (refractive index $n \sim 2.058$), the guided optical modes are penetrated out of the LN core in the Ta_2O_5 -clad waveguide compared to the air-clad waveguide. The LN core power confinement factors Γ for both waveguides are also calculated and labelled in Figure 1(d) and (e).

To characterize the gain performance of the LNOI waveguide amplifier, ~ 10 cm long LNOI waveguides with folded race-track footprint are fabricated and the signal enhancement method is adopted with the experimental schematic shown in Figure 2. The pump light at 976 nm is provided by a diode laser (CM97-1000-76PM, Wuhan Frelink Opto-electronics), while a continuous-wave C-band tunable laser (TLB 6728, NewFocus) with the wavelength range from 1520 to 1570 nm is used as the signal. The pump and signal waves are combined (separated) by the fiber-based wavelength division multiplexers (WDM) with their respective polarization states being adjusted using in-line fiber polarization controllers at the input (output) port of the integrated amplifier. The combined pump/signal is injected into and coupled out of the amplifier by lensed fibers and bidirectional pumping is employed. The coupling efficiencies of both lensed fibers are measured to be 10 dB (8.4 dB) and 9.4 dB (7.6 dB) per facet for the air-clad and Ta_2O_5 -clad waveguides at the pump (signal) wavelength, respectively. All the powers given below are converted into the injected on-chip powers. The output signals are measured by an optical spectrum analyzer (OSA: AQ6370D, YOKOGAWA). A digital camera photograph of the excited Ta_2O_5 -clad Er^{3+} :LNOI waveguide amplifier is also shown in Figure 2 displaying the clearly

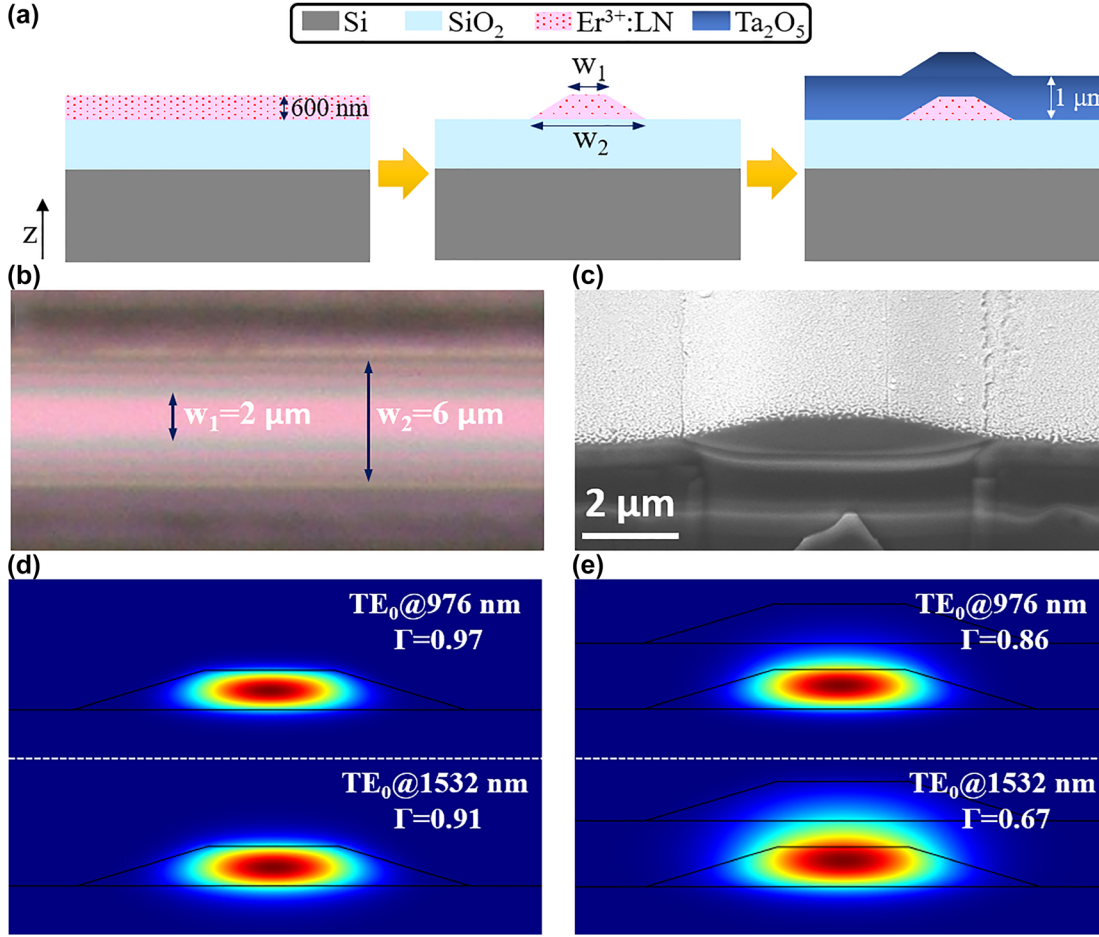


Figure 1: Er^{3+} :LNOI waveguide fabrication and configuration.

(a) Cross-sectional schematic of the Z-cut Er^{3+} :LNOI wafer, the fabricated LNOI waveguide, and the Ta_2O_5 -cladding on top of the LNOI waveguide. (b) Top view microscope image of the air-clad LNOI waveguide. (c) SEM image of the Ta_2O_5 -clad LNOI waveguide cross section. (d and e) The simulated fundamental TE modes for the air-clad and Ta_2O_5 -clad waveguides at the pump and signal wavelengths. The power confinement factor Γ is labelled in each panel.

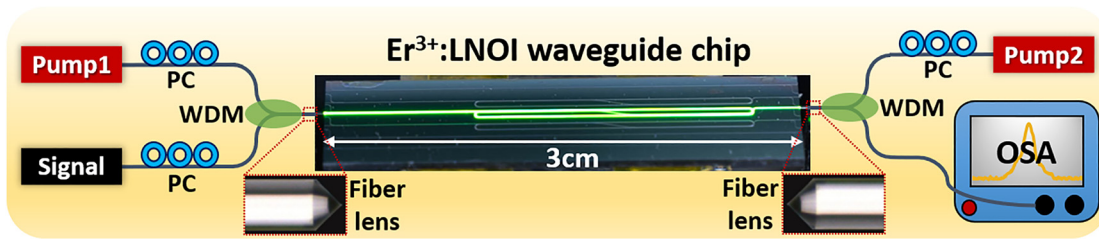


Figure 2: The experimental setup for optical gain measurement. PC, polarization controller. WDM, wavelength division multiplexer. OSA, optical spectrum analyzer. The digital camera photograph of the excited Er^{3+} :LNOI waveguide chip is shown in the center.

visible green upconversion fluorescence from erbium ions along the full waveguide length.

The optical gain of the LNOI waveguide amplifiers with/without Ta_2O_5 cladding is first measured at an injected signal power about -22 dBm and variable pump powers. The signal wavelength is tuned to 1532 nm corresponding to the peak absorption and emission cross sections of erbium

ions [27]. The internal net gain of the amplifier is deduced from the signal enhancement factor as:

$$G = 10 \log_{10} \frac{S^w}{S^0} - \alpha L$$

where S^w (S^0) is the output signal power with (without) pump, α is the propagation loss experienced by the signal

alone including both the scattering loss as well as the absorption loss, L is the waveguide length.

The measured small signal internal net gain for both waveguides is plotted in Figure 3, where red circles represent gain values from Ta₂O₅-clad waveguide and blue squares denote gain values from air-clad waveguide. The signal propagation loss used to deduce the internal net gain is estimated from the resonator-loss measurement of the Er³⁺:LNOI whispering-gallery-mode (WGM) microcavity fabricated using the same LNOI wafer without Ta₂O₅ cladding. The optical transmission curve around the resonant wavelength of 1532 nm is also depicted in the inset of Figure 3 which gives an intrinsic quality factor of $Q \approx 4 \times 10^5$. Thus, the propagation loss at $\lambda = 1532$ nm is obtained by $\alpha = 2\pi n_g / (Q\lambda)$ as 0.98 dB/cm, with the group index $n_g = 2.2$ deduced from the free spectral range measurement. It is assumed that the measured propagation loss being dominated by the absorption loss from ground-state Er³⁺ since the passive scattering loss should be <0.1 dB/cm due to the employed fabrication method (photolithography assisted chemical etching) which can reduce the waveguide surface roughness down to sub-nanometer scale [25]. Then the signal propagation loss in Ta₂O₅-clad waveguide is scaled by the power confinement factors in the LN core as $\alpha_{\text{TaO}} = \alpha \Gamma_{\text{TaO}} / \Gamma_{\text{Air}} = 0.72$ dB/cm, where Γ_{Air} and Γ_{TaO} are the power confinement factors for the air-clad and Ta₂O₅-clad waveguides, respectively.

It can be clearly seen from Figure 3 that the internal net gain increases rapidly with increasing pump powers and then gradually saturates due to reduced inversion of

erbium ions at high gain regime. Notably, the net gain provided by Ta₂O₅-clad waveguide amplifier is higher than the air-clad amplifier when the injected pump powers are higher than 12 mW, and the maximum net gain from Ta₂O₅-clad amplifier is above 20 dB at the maximum pump power of 63 mW. This observation indicates that the Ta₂O₅ cladding can promote the build-up of higher inversion gain along the 10 cm long waveguide amplifier compared to its counterpart without this cladding (air-clad amplifier). Besides, the maximum internal net gain from the air-clad LNOI amplifier is saturated to ~15 dB, being lower than the air-clad LNOI amplifier previously reported [22]. The inferior performance of the current air-clad amplifier could arise from the inadequate inversion of the 10-cm long waveguides compared to the 3.6-cm long waveguides at identical pump powers.

The gain response for the Ta₂O₅-clad amplifier is further measured at the pump power of 60 mW and variable signal powers. The result is plotted in Figure 4. It can be easily noticed that the internal net gain provided by the amplifier decreases with increasing signal powers, arising from the depletion of excited state erbium ions by stimulated emissions induced by high power signals. Besides, the gain bandwidth of the amplifier is also characterized by tuning the signal wavelengths at small signal powers, featuring a broad net gain from 1525 to 1565 nm with the maximum gain peaked around 1532 nm. This gain bandwidth matches well with the Er³⁺ fluorescence band and the observed gain bandwidths in Er³⁺:LNOI waveguide amplifiers demonstrated recently [20–24].

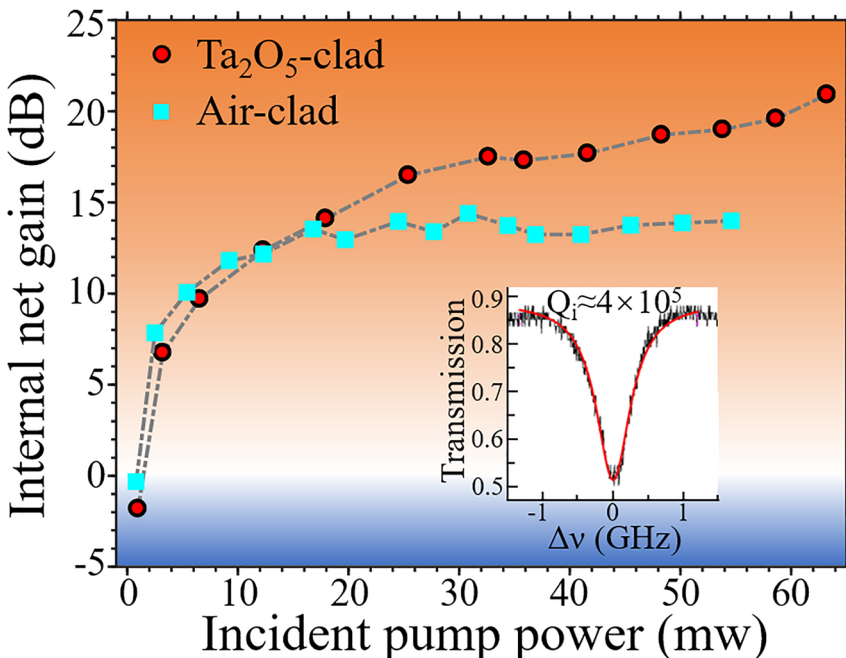


Figure 3: The internal net gain measured from the air-clad (blue squares) and Ta₂O₅-clad (red circles) amplifiers. The optical transmission curve around the resonant wavelength of 1532 nm in the Er³⁺:LNOI WGM-microcavity is shown in the inset.

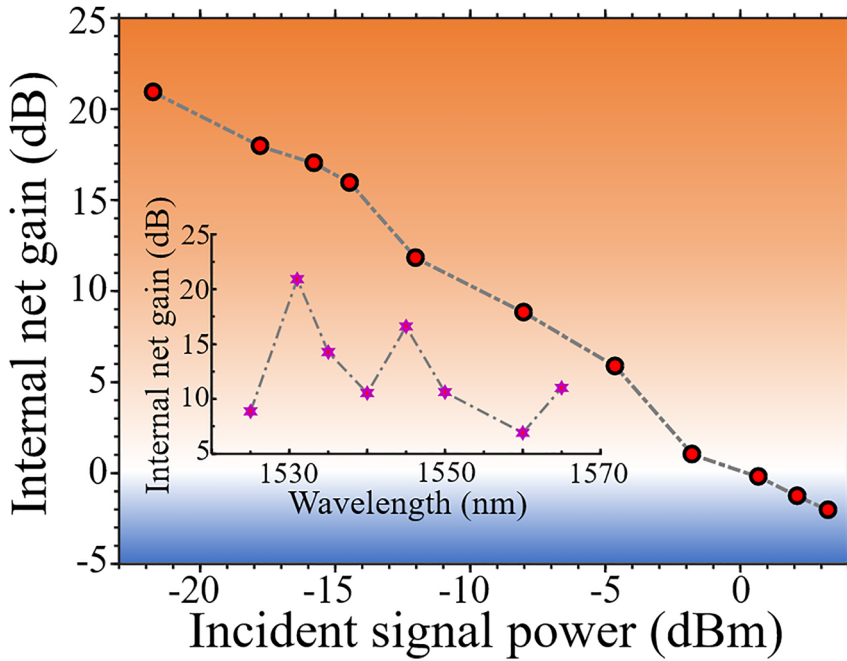


Figure 4: The internal net gain from Ta₂O₅-clad amplifier for increasing input signal powers. The small signal gain values at different signal wavelengths are shown in the inset.

The advantage of the Ta₂O₅-cladding in promoting the optical gain of Er³⁺:LNOI waveguide amplifier deserves a deeper investigation. To this end, an established amplifier model based on the optical mode structures and the steady-state response of erbium ions including the migration-accelerated ETU and the concentration quenching is employed to simulate the gain behaviors of both the Ta₂O₅-clad and air-clad amplifiers [8, 9]. Details about the theoretical model can be found in the supplemental materials. The waveguide length is fixed at 10 cm in the simulation, and the passive propagation loss is set at 0.1 dB/cm. Spectroscopic parameters of Er³⁺ are adopted from the values measured in the Er³⁺-doped bulk LN crystals [27–30].

The optical gain as a function of the input pump and signal powers is first simulated without the contribution of quenched ions for both waveguide amplifiers. The obtained gain values are plotted in pseudo-colors in Figure 5(a) and (b) for the air-clad and Ta₂O₅-clad LN waveguides, respectively. The grey dashed lines in Figure 5(a) and (b) denote the ‘0’ dB gain curves delimiting the practical loss region (blue-shaded) and gain region (red-shaded) in the gain maps. Identical behaviors can be observed with comparable gain values for both waveguide amplifiers.

The gain behaviors of both amplifiers including the contribution from quenched ions are further investigated. The gain values obtained by supposing 20% of active ions are fast quenched are depicted in pseudo-colors in Figure 5(c) and (d), where the grey ‘0’ dB curves delimit the gain and loss regions as well. It can be clearly seen that

the presence of quenched ions greatly reduces the optical gain, due to their detrimental absorption of the pump and signal powers without contributing to the inversion gain. Moreover, it can be noticed that both the maximum small signal gain and the area of practical gain region are larger for the Ta₂O₅-clad amplifier compared to that of the air-clad amplifier. To be more specific, the small signal gain at a fixed signal power (–25 dBm) and increasing pump powers and the signal gain at a fixed pump power (50 mW) and increasing signal powers are plotted in Figure 5(e) and (f) for both waveguide amplifiers with three different fractions of quenched ions $f_r = 0, 10, 20\%$, respectively. It can be easily inferred from the gain curves that, besides the normal gain saturation behaviors due to the depletion of inversion gain by the pump and signal at high powers, the optical gain provided by Ta₂O₅-clad amplifier is higher than the gain by air-clad amplifier at larger fractions of quenched erbium ions. Since the quenched ions are unavoidable in the Er³⁺:LNOI amplifier with high doping concentration, the simulation results indicate the better gain response of Ta₂O₅-clad amplifier than the air-clad amplifier in practical conditions.

The revealed gain responses from the simulation results match qualitatively with the observed gain dynamics and superior gain performance of the Ta₂O₅-clad amplifier compared to the air-clad amplifier, though a quantitative agreement between experiment and simulation necessitates further characterizations of the spectroscopic response of Er³⁺ in the ion-sliced LN thin film and the fraction of quenched ions which is beyond the scope of current work. Nevertheless,

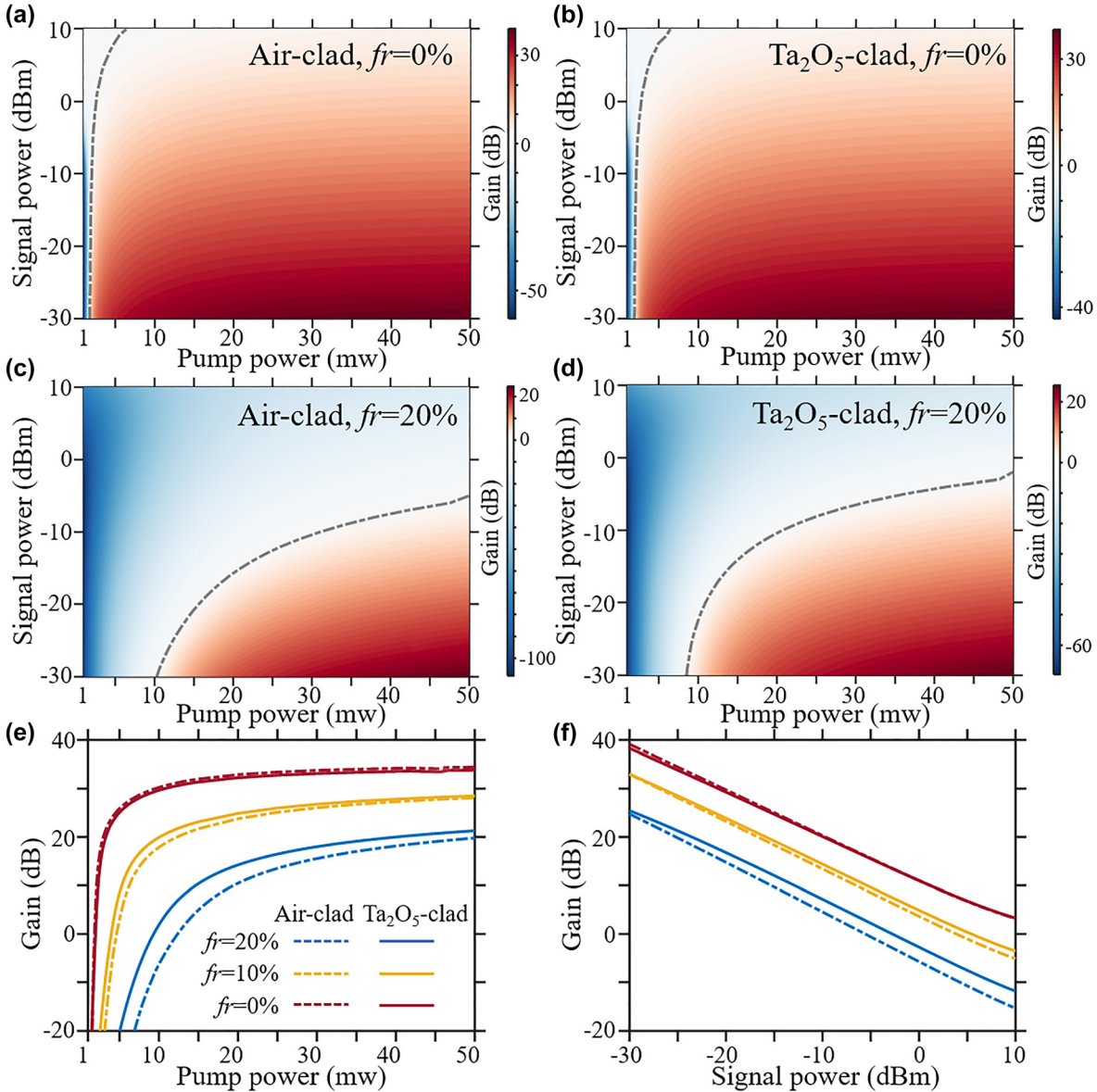


Figure 5: The simulated gain response for both waveguide amplifiers.

The gain map calculated at each pair of signal and pump powers is depicted in pseudo-colors for air-clad amplifier (a) and (c), Ta₂O₅-clad amplifier (b) and (d). The fractions of quenched erbium ions are labelled in each panel. The gain curve versus pump power and the gain curve versus signal power are plotted in (e) and (f). The same figure legend is applied for (e) and (f).

the above simulation pinpoints the role of cladding in reducing the counteracting effect by quenched ions, which can be understood by considering the mode structures in both waveguide amplifiers. A moderate fraction of optical power is guided outside the active LN core in the Ta₂O₅-clad waveguide, which can be immune from the detrimental absorption of pump and signal powers by the quenched ions. Though the guided power in the core is lower which decreases the peak intensities and thus the population inversion gain, this reduction is compensated by the more uniform inversion

along the full waveguide length due to the reduced absorption of pump and probe powers by the quenched ions. Meanwhile, additional simulations have been done for the maximum output signal powers provided by the amplifiers at each pump and signal powers. The saturated power provided by the Ta₂O₅-clad amplifier is also higher than the air-clad amplifier for certain quenched fractions.

The migration-accelerated ETU and the concentration quenching impose an underlying limit to the optical gain provided by erbium ions. The former annihilates excited

erbium ions and reduces the population inversion, while the latter purely absorbs light without establishing gain. Both effects critically depend on the erbium doping concentration and the quality of the doping method. A suitable doping concentration as well as a homogeneous doping process is desired to reduce the migration parameter and the quenched fraction [31]. Meanwhile, the optical pumping of erbium ions should be judiciously controlled to avoid excessive population of excited states, in order to alleviate the ETU process and allowing more efficient gain with long amplification length. Thus, the Ta₂O₅-clad amplifier which confines some fraction of pump power in the cladding can mitigate the excessive excitation of Er³⁺ and achieve higher gain to some extent.

Further power scaling of the Er³⁺:LNOI waveguide amplifier can be conceived by optimizing the cladding materials and guiding geometries. Important clues can be borrowed from the prevalent double-cladding optical fiber design, which allows guiding a large amount of optical power within the inner cladding area which surrounds the much narrow active core [5, 6]. The pump power is progressively absorbed by successive crossing the active core which provides homogeneous inversion gain for the signal mode mainly guided in the core. Shaping the cladding material into waveguiding geometry will allow direct cladding pumping, with the waveguide length for adequate pump absorption depending on the area ratio between the cladding and the active core. For a cladding-to-core area ratio of 10:1 and a pump absorption coefficient of 2 dB/cm estimated from our Er³⁺:LNOI waveguide, the desired double-cladding LNOI waveguide length will be ~1 m. High gain and power performance can be expected from such waveguide due to the high cladding pump power, as long as the passive propagation (scattering) loss is maintained to be low for meter-scale LNOI waveguides.

In conclusion, above 20 dB small signal internal net gain in a Ta₂O₅-clad Er³⁺:LNOI waveguide amplifier has been demonstrated. Experimental characterizations reveal the advantage of Ta₂O₅ cladding in gain performance compared with the Er³⁺:LNOI amplifier without cladding. Theoretical modelling pinpoints the role of cladding in mitigating the quenched ion absorption and providing better gain performance for the Er³⁺:LNOI waveguide amplifier. The demonstrated high-gain Er³⁺:LNOI amplifiers hold great promise in a broad spectrum of applications such as optical communication, integrated microcomb and precision metrology.

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