Giant Optical Gain in a Rare-Earth-Ion-Doped Microstructure

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Semiconductor optical waveguide amplifiers deliver high gain per unit length (up to ~1000 dBcm^{-1}),[1,2] enabling light amplification over short distances in photonic integrated circuits.[3] In contrast, rare-earth ions are regarded as impurities providing low gain (up to ~10 dBcm^{-1}),[4–7] because electronic transitions within their 4*f* subshell are parity forbidden, dictating low transition probabilities and cross-sections. Nevertheless, devices such as fiber amplifiers and solid-state lasers profit from accordingly long excited-state lifetimes–hence increased excitation densities–in rare-earth-ion-doped materials, combined with large device lengths. Here we exploit the extreme inversion densities attainable in rare-earth-ion-doped microstructures in a host material, potassium double tungstate,[8] that provides enhanced transition cross-sections and dopant concentrations,[9,10] thereby demonstrating a gain of 935 dBcm^{-1} in channel-waveguide and 1028 dBcm^{-1} in thin-film geometry, comparable to the best values reported for semiconductor waveguide amplifiers. Further improvement seems feasible with larger dopant concentrations. This gain is sufficient to compensate propagation losses in plasmonic nanostructures,[11,12] making specific rare-earth-ion-doped materials highly interesting for future nanophotonic devices.

Amplification of optical signals is required whenever the concentrations. The typical gain per unit length reported for rare-earth-ion-doped integrated waveguides has hardly exceeded a few dB cm^{-1}.[4–7]

Semiconductor optical amplifiers (SOAs), including organic semiconductors,[13,14] and III–V semiconductors,[15–19] with different gain structures, such as quantum wells (QW),[15,16] multiple quantum wells (MWQ),[17] and quantum dots (QD),[18] deliver high gain over short distances, which in combination with heterogeneous integration techniques, make SOAs suitable for providing on-chip gain. However, due to the short carrier lifetime in these materials and significant refractive-index changes accompanied with the excitation of electron-hole pairs, temporal and spatial gain patterning effects limit their performance. Also dye-doped optical amplifiers (DOAs) can deliver high gain per unit length.

The enormous difference in gain per unit length provided by these materials originates in their physical properties, as exemplified in **Table 1**. The relevant performance parameter, their modal gain (dBcm^{-1}),

$$g_{mod} = \Gamma g_{mat} = 4.34\Gamma(\sigma_{em} N_2 - \sigma_{abs} N_1) \approx 4.34\Gamma\sigma_{em} N_{inv} \quad (1)$$

is given by the fractional overlap (or mode-confinement factor)