Design of high-gain, small-footprint ytterbium-doped potassium double tungstate waveguide amplifier for short-distance optical interconnects

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Ytterbium (Yb^{3+})-doped potassium double tungstate (KYW) is a promising material for optical amplification due to its high and broad gain characteristics around 1 μm wavelength. The KYW channel waveguide amplifier coupled to fiber ends with mode field diameter of 6 μm is optimized. Numerical results show that for 53.5 at. % Yb^{3+} doping over 50 dB fiber-to-fiber gain is attainable in single mode channel waveguide designs with layer thickness and channel width less than 7 μm and 11 μm respectively. The optimum device length being as short as 1 mm is highly promising for short-distance optical interconnects with stringent device footprint requirement.

Introduction

With the ever increasing demand on data transmission speed, optical interconnects have become a promising solution not only for the conventional long-haul transmission systems, but also for shorter reach rack-to-rack, board-to-board, and on-board systems. These short-distance optical interconnects typically require optical amplifiers to compensate for losses at various stages. Since the device footprint is critical for these applications, optical amplifiers being capable of delivering high gain over a small device dimension are needed.

The rare-earth-doped fiber amplifier, which is the workhorse of high-speed long-haul communication systems, exhibits device length ranging in meters. Direct downscaling of the fiber amplifier for short-distance optical interconnects would inevitably necessitate high rare-earth-ion dopant concentrations. Consequently, complex energy transfer mechanisms become significant, which in turn deteriorate the overall gain performance [1]. The semiconductor optical amplifiers (SOAs), on the other hand, can easily provide device lengths on the order of millimetres. Nevertheless, the amplification bit-rate of conventional quantum-well SOAs is limited by its inherent gain recovery time and lower dimension quantum-dash or quantum-dot structure will be needed to amplify high-speed optical signal [2].

Recently, our group has demonstrated that potassium double tungstate doped with 47.5 at. % of ytterbium (Yb^{3+}) could provide record modal gain up to about 1000 dB/cm [3] and more than 150 dB/cm of gain across a bandwidth of 55 nm ranging from 977 nm to 1032 nm wavelength [4]. In this paper, we report on the design of channel waveguide amplifiers exploiting the high and broad gain features of potassium double tungstate (KYW) doped with ytterbium-ion concentration as high as 53.5 at. %. The cross section of the channel waveguide and the amplifier's length are optimized. To probe into realistic gain achievable by the amplifier, fiber-to-fiber gain is considered by taking into account the coupling losses of the optical pump and signal at the two ends of the amplifier.

Numerical Calculation

The layout of the channel waveguide amplifier is schematically depicted in Figure 1. A 53.5 at. % Yb-doped KYW active layer is sandwiched in-between an undoped $KY(WO_4)_2$ substrate and a $KY(WO_4)_2$ overgrown layer. It is co-doped with optically inert Gd^{3+} and Lu^{3+} ions to match the lattice constant of the substrate [4]. The etch depth of the channel waveguide is fixed at 1.5 µm in accordance to the etching process developed previously in our group. The variables in the optimization study are the channel width, *w* (4-10 µm), the active layer thickness, *t* (4-8 µm), and the device length, *l* (0-1.5 mm). Material properties of the active layer such as the refractive index as well as the absorption and emission cross sections are assumed to be the same as those of 47.5 at. % Yb-doped potassium double tungstate [3]. The fiber-to-fiber gain is simulated using Phoenix FieldDesigner [5] considering that the 932 nm optical pump and the 981 nm optical signal are coupled into/out of the amplifier from fiber ends with mode field diameter of 6 µm.

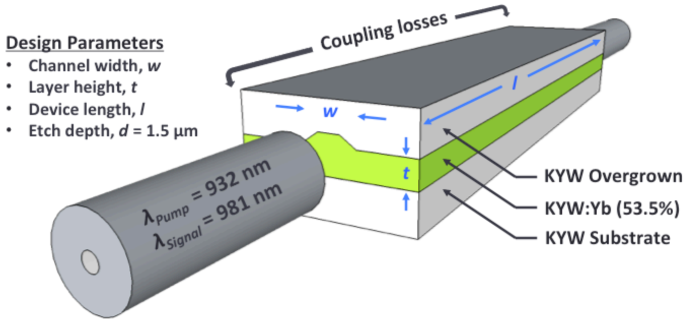

Figure 1: Schematic of the structural design of the channel waveguide amplifier.

Results

Figure 2 shows the maximum channel width, w_{max} permitting single transverse electric (TE) mode for channel waveguide with active layer thickness, *t*. The ridge structure provides better lateral confinement for thinner waveguides, hence resulting in smaller w_{max}.

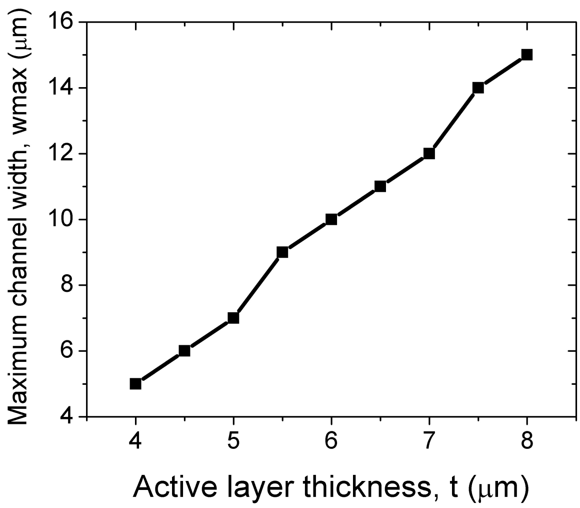

Figure 2: Maximum single-mode channel width, w_{max} as a function of waveguide thickness.

The in- and out-coupling power losses can be calculated from the overlap integral between the Gaussian mode field of the fiber and the mode field of the waveguide (Fig. 3). The slopes in Fig. 3 indicate that the mode overlap values are more sensitive to the variation of w as t increases. In other words, amplifiers based on thicker active layers are expected to be less tolerant to fabrication errors and more sensitive to fiber misalignment than those with a thinner active layer.

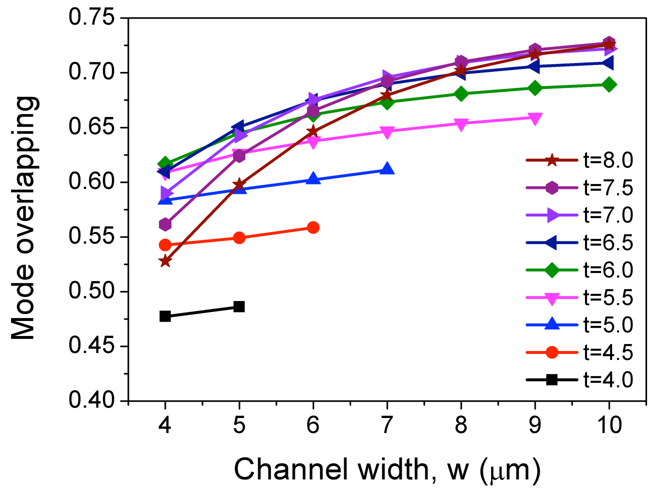

Figure 3: Overlap integral between the modal fields of the fiber and amplifier waveguide. The data for w exceeding w_{max} (i.e. those supporting multi-modes) is not shown in the figure.

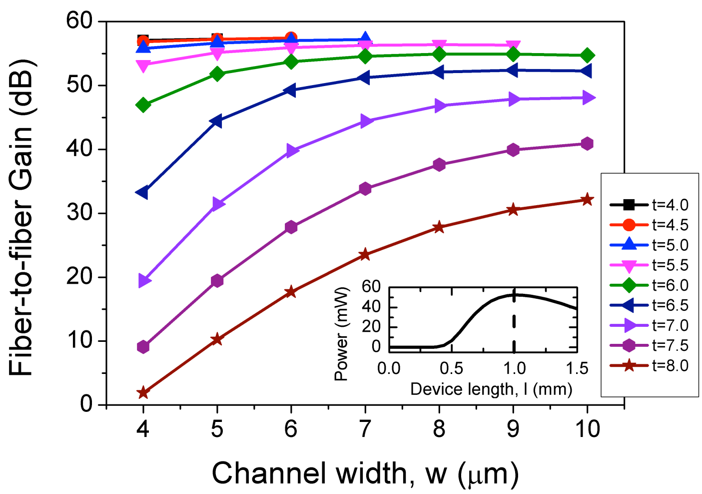

Figure 4: Simulated fiber-to-fiber gain for single-mode waveguide amplifier. Inset shows the evolution of the signal powers to the propagation distance for amplifier with $w = 4.0$ and $t = 4.0$

The fiber-to-fiber gain (G_{f2f}) is determined by taking into account the in-coupling power loss, the internal gain of the waveguide amplifier, and the out-coupling power loss. It is calculated from the signal powers in the output fiber, $P_{fiber,out}$ and the input fiber, $P_{fiber,in}$,

$$G_{f2f} = 10\log\left(\frac{P_{fiber,out}}{P_{fiber,in}}\right).$$

Figure 4 shows the simulated G_{f2f}. Each data point represents the highest gain attainable for the given waveguide dimension at optimum device length. As oppose to the trend in Fig. 3, amplifiers with thin active layers are found to exhibit high G_{f2f} despite poor mode overlap with the fibers. The amplifiers with small core have better internal gain and their corresponding optimum device lengths are slightly longer than those with larger core design. Over 50 dB fiber-to-fiber gain is attainable for most of the simulated amplifier waveguide designs in the regime of $t < 7$ µm and $w < 11$ µm. A sample of the evolution of signal's power to the device length is shown in the inset of Fig. 4. The optimum device length is found to be as short as 1 mm.

Conclusions

The design of a 53 at. % ytterbium-doped potassium double tungstate waveguide amplifier is studied and optimized. Numerical results show that fiber-to-fiber gain of over 50 dB is achievable for amplifiers as short as 1 mm. Such high-gain, small-footprint amplifiers are highly promising for short distance optical interconnects.

References

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