Study of Sharp Bends in Anisotropic Potassium Double Tungstate Waveguides

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ABSTRACT
Rare earth ion doped potassium double tungstate gain materials have recently shown a great promise for the development of waveguide amplifiers and lasers exhibiting excellent performance. To enable the use of this material in larger nanophotonic platforms, sharp bends are required.

In this work we study the effect of the anisotropy of potassium double tungstates on the bend losses of high contrast waveguides using three different simulation methods. It is concluded that the existence of this anisotropy has not detrimental effect on the bend losses, therefore opening the door to the utilization of this material for integrated nanophotonics.

Keywords: potassium double tungstates, rare-earth ions, sharp bends, anisotropic material, monoclinic, finite differences, FDTD.

1. INTRODUCTION

The increased demand for performance and capacity in datacoms, short-distance optical links and next generation exascale computer systems is pushing the requirements of electronics to physical limits, especially due to the bandwidth and power consumption limitation of electrical metallic interconnects. Integrated photonics has emerged as a possible way of overcoming these limitations. As an increasingly large number of photonic components are integrated onto the same chip, optical losses become significant. On-chip amplifiers, ideally capable of amplifying very high rate signals, become a necessity. Other application fields such as optical-coherent communications, trace-gas detection and optical beam-forming just to name a few, will greatly benefit from high power on-chip micro-lasers with tunable output wavelengths.

The family of potassium double tungstates hosts, $KY(WO_4)_2$, $KGd(WO_4)_2$ and $KLu(WO_4)_2$, doped with rare-earth (RE) ions are very good candidates for such applications. The long excited state lifetime of the RE ions, typically in the millisecond range, permits the amplification without distortion of high rate signals. The RE ion dopant concentration in these materials can be made considerably larger than in amorphous hosts due to the large interatomic distance (~0.5 nm) between RE ions, which prevents severe lifetime quenching. The possibility of high RE on dopant concentration together with the very large absorption and emission cross-sections of RE ions in these host materials [1], permits achieving large gain values. This is especially interesting in waveguide configurations, in which, thanks to the large overlap of pump and signal beams, modal gains as high as ~1000 dB/cm have been experimentally demonstrated [2]. Low threshold, high power, low quantum defect [3][4] integrated micro-lasers have been developed in Yb^{3+} doped double tungstates, which, due to the broadband emission of the RE ions, can be tuned over a wavelength range of close to 100 nm. High output power, 1.6 W, with 80% efficiency, has been demonstrated in waveguide lasers in Tm^{3+} doped double tungstates [5] at a wavelength of 1840 nm.

However, these are demonstrations of isolated devices made in low contrast optical waveguides in which the refractive index difference between core and cladding is of $\sim 2\times10^{-2}$. In order for RE-ion doped double tungstate waveguide lasers and amplifier devices to find widespread acceptance in integrated photonics, their size should be minimized and should be integrated with more optical functions on a chip. High index contrast waveguides should be used to reduce the size of RE-ion doped double tungstate devices. The high index contrast permits reducing the core dimensions increasing the electromagnetic field intensity inside the material. This way, higher RE-doping concentrations can be inverted and a higher gain per unit length is achieved thus reducing the overall length of the devices. Sharp bends are also an indispensable device to achieve high level of integration. High index waveguides will permit reducing the radius of curvature of waveguides bends while maintaining low bend losses. Preliminary efforts towards the realization high index contrast waveguides in potassium double tungstates by means of the heterogeneous integration of this material onto silica substrates have been recently reported [6]. Potassium double tungstates are patterned by ion beam etching (IBE) [2]-[5] and focused ion beam [6] to produce low loss waveguides. Once thin layers of this material can be successfully transferred onto different passive substrates, many interesting devices can potentially be developed. However, the family potassium double tungstate materials crystallize in the monoclinic crystal system [7]. They present three crystalline axes and three optical axes. The refractive indices at a wavelength $\lambda = 1.55$ μm and for the material composition chosen for this work, $KYb_{0.475}Gd_{0.447}Lu_{0.078}(WO_4)_2$, are summarized in Table 1. Bends in potassium double tungstates have not been yet reported.

Table 1. Refractive indices along the three optical axes of $KYb_{0.475}Gd_{0.447}Lu_{0.078}(WO_4)_2$. Measurements taken using a Metricon prism coupling system [7].

Axis	Refractive index
N_m	2.0149
N_p	1.9795
N_g	2.0618

In this work, we numerically characterize the performance of bent waveguides in potassium double tungstate gain materials using three commercial software packages. The first one, FieldDesigner two dimensional mode solver from PhoeniX B.V. [8], permits to realize the calculation of bend losses in waveguides with isotropic dielectric constant. The second one, Mode Solutions from Lumerical [9], permits to calculate bend losses introducing a diagonal matrix for the dielectric constant. Finally, three dimensional finite difference time domain (FDTD) software, FDTD Solutions from Lumerical [9], was utilized to simulate the bend losses considering the three optical axes. The bend losses as a function of radius of curvature for $KYb_{0.475}Gd_{0.447}Lu_{0.078}(WO_4)_2$ have been calculated. It was concluded that the presence of the anisotropy in this material does not present a detrimental effect on the bend losses, enabling a full range of devices to be fabricated.

2. DESCRITPION OF THE STRUCTURE

Figure 1 shows the structure of the waveguide considered in this work. A ridge in $KYb_{0.475}Gd_{0.447}Lu_{0.078}(WO_4)_2$ with dimensions $0.85\times0.85\ \mu m^2$ was considered. A thin adhesive layer is utilized to bond the thin $KYb_{0.475}Gd_{0.447}Lu_{0.078}(WO_4)_2$ layer onto a silica (SiO_2) substrate [6]. The adhesive layer utilized is BCB, with refractive index 1.535 at $\lambda = 1.55\ \mu m$ and thickness of 100 nm. The orientation of the optical axes of the double tungstate in the ridge is also indicated.

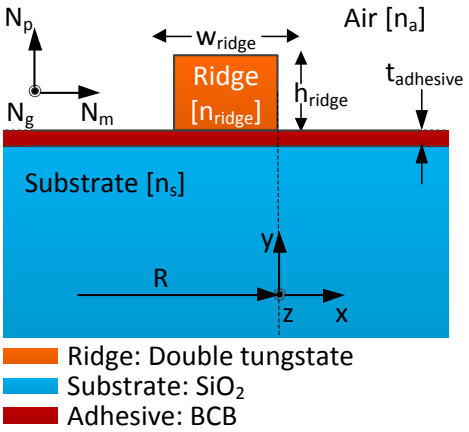

Figure 1. Structure used for the simulations, showing the three optical axes of the double tungstate (ridge) as well as the definition of the radius of curvature. Parameters of the structure: $w_{ridge}=h_{ridge}=0.85\ \mu m$; $n_s=1.444$; n_{ridge} (see Table 1), $n_{adhesive}=1.535$, $t_{adhesive}=100$ nm.

3. SIMULATIONS

3.1 Two dimensional simulations using PhoeniX FieldDesigner mode solver

A full vectorial finite differences (FD) method was utilized in the FieldDesigner module of PhoeniX B.V. In this method, PhoeniX software automatically adjusts the size of the grid cells near the edges of simulated objects and at large refractive index steps. It also enforces at least one grid cell inside every object. Due to the large difference in the thickness of the different layers of the structure, it is very important to have enough number of grid cells inside the thinner layers while maintaining the overall simulation time reasonable. To achieve this goal, the thinner layer in the structure, the adhesive layer, was artificially built of thinner layer of the same material. In this way, a finer grid is obtained at the desired locations. Since PhoeniX FieldDesigner cannot handle anisotropic materials, the refractive index of the N_m optical axis was utilized for the TE-mode and the refractive index of the N_p axis for the TM-mode. However, since the modes in a channel waveguide are not pure TE or TM but they present small components along the other axes (quasi-TE mode and quasi-TM mode), it is expected that a small error in the simulations will be introduced by using an isotropic model. In the simulations, the adhesive layer (100 nm thick) was divided into 30 sublayers. Convergence tests were ran to ensure that the selected number of grid points was sufficient. A grid of 129××129 points with a window size of 3.7 μm width by 4 μm high was utilized.

In order to calculate the bend losses of the structure as a function of bend radius, a script was written that first calculates the straight modes of the structure ($R = \infty$). The radius is then decreased step by step. For each new value of the radius, the supported modes are identified by selecting the modes that maximize the overlap with the modes found for the previous value of bend radius. Figure 2 shows the two modes (TE-mode and TM mode) obtained for the structure of Fig. 1 for a radius of 2 μm.

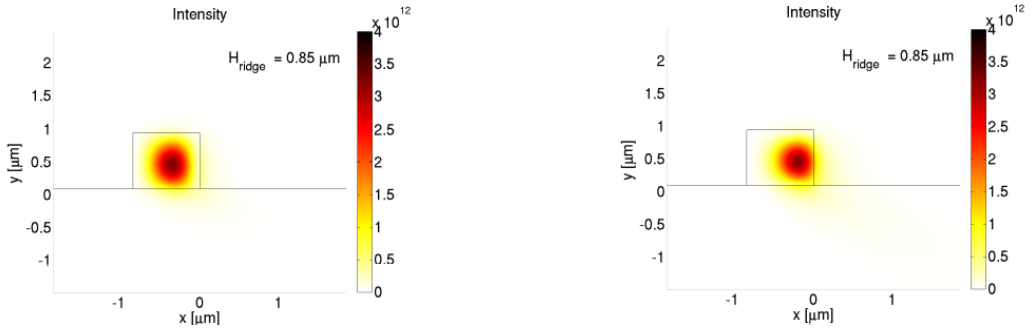

Figure 2: (a) TE-Mode; (b) TM-mode. Simulation parameters: R =2 μm, λ =1.55 μm, ridge dimensions 0.85 × 0.85 μm.

3.2 Two dimensional simulations using Lumerical MODE Solutions

Lumerical MODE solutions was used to calculate the bend losses of the structure depicted in Fig. 1 taking into consideration the two optical axes perpendicular to the direction of propagation (*i.e.*, N_m and N_p). The size of the simulation window was chosen identical to the one in the previous section (3.7×4 μm^2). The grid was chosen uniform (11 nm in the y-axis, 10 nm in the x-axis) with a mesh override on the thin adhesive layer in the y-axis (4.5 nm).

3.3 Three dimensional simulations using Lumerical FDTD Solutions

Figure 3 shows the setup utilized for the 3-D FDTD simulations. The three optical axes were considered in the ridge. A mode of the bend structure was injected into the waveguide (Mode source in Fig. 3). The mode was propagated over a 270 deg bend to prevent radiative modes to be caught by the power monitors. A straight waveguide segment was added after the 270 deg bend to permit the fields to smoothly propagate out of the simulation window. Because the 3-D FDTD simulations are very resource consuming, it is important to optimize the size of the simulation window and grid size. A uniform grid size of 16 nm was utilized. No mesh override was used in this case, due to the increase on computation resources.

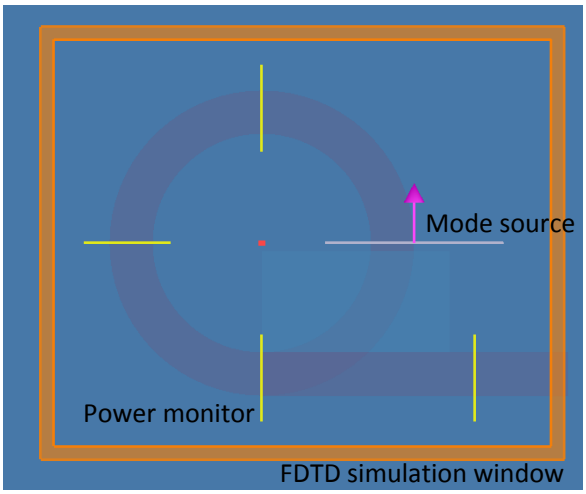

Figure 3. Simulation setup for 3-D FDTD simulations.

4. RESULTS

In order to verify that the settings in the three simulation methods were correct, bend losses as a function of radius were calculated for the isotropic structure, considering the refractive index of N_m axis (Table 1) for the ridge. Figure 4(a) shows the results of this simulation. It can be seen that the losses calculated by the three methods are equivalent.

The bend losses for the isotropic material (calculated by PhoeniX FieldDesigner), two-axes (Lumerical MODE) and three axes (Lumerical FDTD) are depicted in Fig. 4(b). It can be seen that adding the second axis, N_p, into the simulations introduces negligible differences. The third axis in the propagation plane, N_g, slightly decreases the losses for small radii. A possible explanation is that the mode traveling in the ridge experiences a slightly higher effective refractive index due to the higher refractive index of the N_g axis. However, the small differences observed could be due to a slightly rougher mesh used in the FDTD simulations due to high computation resources requirements of 3-D FDTD. However, it is possible to conclude, that the three axes of the double tungstate gain material do not seem to have a detrimental effect in the bend losses of the waveguide structure proposed in this work.

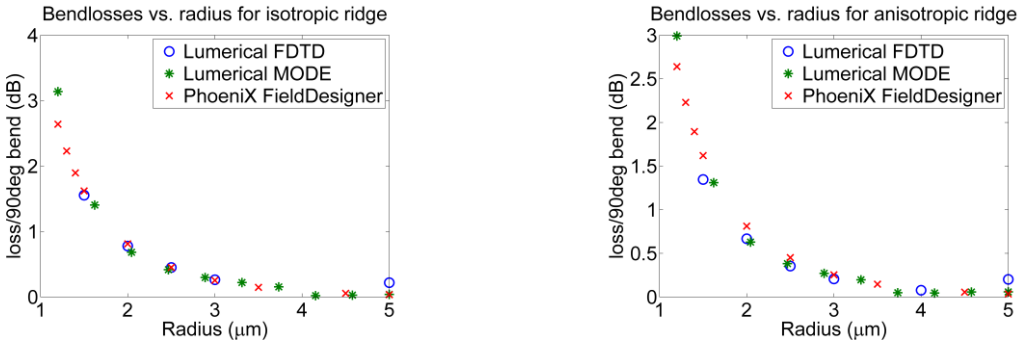

Figure 3. Bend losses in dB/90deg bend of the TE-mode of the structure of Fig. 1 as a function of bend radius. An isotropic structure was considered for the ridge, with a refractive index corresponding to the N_m. axis. Comparison of the results between PhoeniX FieldDesigner, Lumerical Mode and Lumerical FDTD Solutions. (b) Effect of the anisotropy of the double tungstate ridge material on the bend losses.

5. CONCLUSIONS

The effect of the optical anisotropy of rare earth potassium double tungstate gain materials on bend losses have been studied using three different methods. The presence of the three optical axes does not appear to introduce detrimental effects on the propagation losses. This opens up the door to the realization of interesting integrated photonic devices in rare earth ion doped double tungstate high contrast waveguides, such as ring lasers or spiral waveguide amplifiers.

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