Effects of nonlinear losses and design geometry on gain in silicon waveguides with erbium doped regions

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Abstract: We investigate the effects of design geometry and nonlinear losses on gain in silicon with erbium-doped regions. Multi-trench designs distribute intensity more uniformly and reduce the nonlinear losses including up conversion and excited state absorptions.

OCIS codes: (230.7370) Waveguides; (130.4310) Nonlinear

1. Introduction

Silicon light emitters are missing links for future silicon based photonic integration. The challenge is to attain high quantum efficiency of silicon light emitters. Many approaches have been enabled to obtaining gain of silicon ranging from silicon nanocrystals to erbium doped silicon [1-2]. However, adverse effects including erbium solubility induce considerable reduced emission in the telecommunication wavelength (~1.5μm). Low-index host material such as oxide glass (phosphosilicate and soda-lime glasses), ceramic thin films (Al_2O_3, Y_2O_3) can also be doped with erbium to provide light amplification at near infrared wavelength [3]-[4]. Different schemes of confining light in low-index structures have been presented to achieve CMOS compatible light emitting devices. Silicon slot waveguides, sub-micrometer slot embedded in between waveguides, have been experimentally demonstrated to provide a high optical confinement in the slot region as well as future possible optical gain [5]-[6]. Recently, stochiometric single-crystal Er_2O_3-on-Si grown by atomic layer epitaxy is realized to further develop multi-component rare-earth oxides.100-fold increase in Er $^{3+}$ concentration over conventional Er-doped glasses is achieved [7], making it a promising material for light amplification in the near-infrared wavelength. However, the ultimate gain in erbium doped glass matrix on silicon is determined by complex interplay between multiple loss parameters which needs to be evaluated individually.

We present a theoretical study on nonlinear loss and gain competition in erbium doped matrix in multi-trench silicon waveguides. We study the effects of power distribution profile on excited state absorption and up-conversion in erbium doped active regions, as well as nonlinear loss mechanisms in silicon. Results indicate that distributing energy over multi-trench configuration mitigates the effect of up-conversion and excited state absorption losses. Nonlinear losses of erbium as well as silicon are reduced by the splitting the erbium region area into more subareas; in other word, more trenches. As a result, multi-trench configurations generating up to 0.9dB/cm higher signal amplification with respect to a single trench configuration of the same erbium doped area.

2. Device geometry and theoretical model

The analyzed device structure of a silicon rib waveguide with multiple erbium-doped active regions is illustrated in Fig. 1(a). In the below structures, silicon (refractive index n_{si}=3.48) rib waveguide acts as a platform with rectangular low-index erbium doped Al_2O_3 ($n_{Er\text{-}Al2O3}$ =1.64) regions and silicon dioxide (n_{sio2}=1.45) as a cladding layer. Normalized power distribution (W/m^2) profiles of the structures are computed by finite element analysis using COMSOL multiphysics software. Quasi-TE mode of a waveguide with four erbium doped active regions is shown in Fig.1 (b). Different loss mechanisms in analyzed structures will also be discussed. Loss mechanisms as in Fig.1(c) include excited state absorption, cooperative up conversion, linear loss in the erbium doped Al_2O_3 regions and free carrier loss, linear loss in the silicon regions.

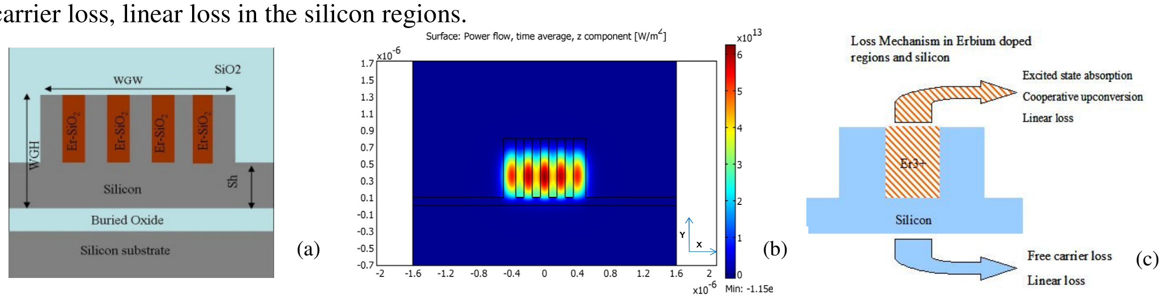

Fig. 1. (a) Geometry of a silicon waveguide with multiple rectangular Erbium-doped active regions.
(b) Normalized power distribution (W/m^2) of quasi-TE mode of a waveguide with four erbium doped active regions.
(c) Loss mechanisms in proposed structures of silicon waveguides with erbium doped active regions.

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The analyzed geometry designs include two different groups (WG1 and WG2) of waveguide dimensions investigated in detail as shown in Fig. 2 for cross section view. Waveguide height is fixed at 0.8µm, while waveguide width is 0.6µm for WG1 and 1.0µm for WG2. Since trench width is 0.1 µm due to fabrication capability. Two waveguide groups are assessed in this paper. For WG1 in Fig 2 (a), two subgroups single trench (WG1A) and two trenches (WG1B) configurations are proposed, while for WG2 in Fig 2 (b), two trenches (WG2A) and four trenches (WG2B) are analyzed. Waveguide length is selected as 1cm in all structures. For the same waveguide dimension, the total erbium-doped active area remains the same for different number of active regions. Also, to assess the net effect of nonlinear losses, the linear loss is ignored.

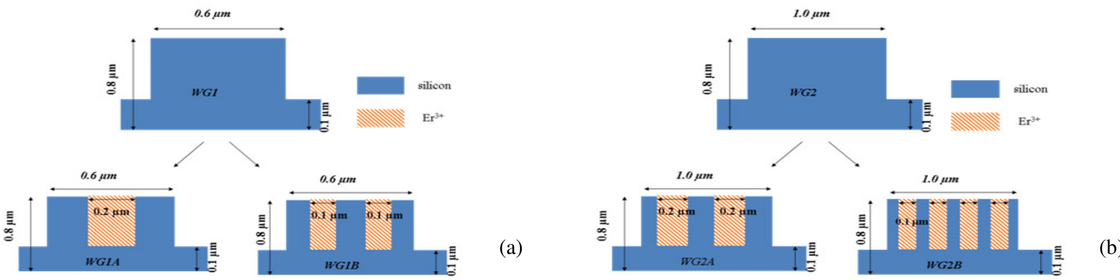

Fig .2. (a) Illustrations of WG1 of waveguide dimensions (0.6 µm width, 0.8 µm height, 0.1 µm trench width)
(b) Illustrations of WG2 of waveguide dimensions (1 µm width, 0.8 µm height, 0.1 µm trench width)

Theoretical model and erbium related parameters in the paper in based on four-level rate equation taking into account of cooperative up conversion at 1.48 µm pumping wavelength [8]. In this analysis, 1.48 µm pumping is the only feasible wavelength with the presence of silicon waveguide. Also, Erbium concentration is optimized for the proposed designs as 5e21 cm^{-3}.

3. Results and Discussions

Excited state absorption and cooperative upconversion coexist in erbium doped regions in the proposed structures. In the simulations, we eliminate excited state absorption "NoESA(UP only)" when cooperative up conversion effect is studied and vice versa "NoUp(ESAonly)". As in Fig .3(a) for WG1A, excited state absorption is more pump power dependent and predominate at higher pump powers, while up conversion limit the ultimate signal enhancement up to 10dB. For waveguide group WG1 in figure 2, we compare the performances of the two subgroups and calculation is based on the same total erbium doped trench areas and equal pump power. As in Fig .3(b) and (c), excited state absorption as well as up conversion are more dominant in the single trench structure as opposed to double trench structure. The results show up to 3.5dB gain improvement in double trench design. Multi-trench configuration can distribute the pump more uniformly in the total active regions; thus, reduce the pump intensity locally to mitigate the adverse effects.

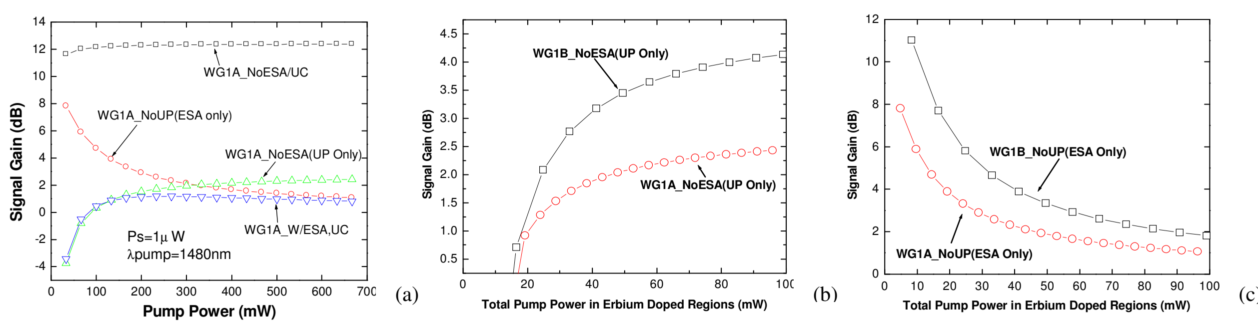

Fig .3 (a) Signal gain of WG1A versus pump power with different loss mechanism in erbium doped regions.
(b) Effect of up conversion (no ESA) on signal gain of WG1A and WG1B versus total pump power in the erbium doped regions.
(c) Effect of excited state absorption (no Up) on signal gain of WG1A and WG1B versus total pump power in the erbium doped regions.

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At high pump powers, optical loss induced by free carrier absorption in silicon cannot be neglected [9]. Pump intensity in silicon experiences nonlinear losses induced by free carrier absorption can be expressed by equation 6 in [9]. Simulation results show that free carrier induced loss prevails in single trench configuration (WG1A) than two-trench configuration (WG1B) for the same input coupled pump power in silicon as in Fig .4(a) and the same is for WG2A and WG2B in Fig .4(b). Since free carrier absorption is pump intensity dependent, it can be explained as more uniform intensity distribution for multi-trench configuration by splitting the same silicon regions into more sub-regions.

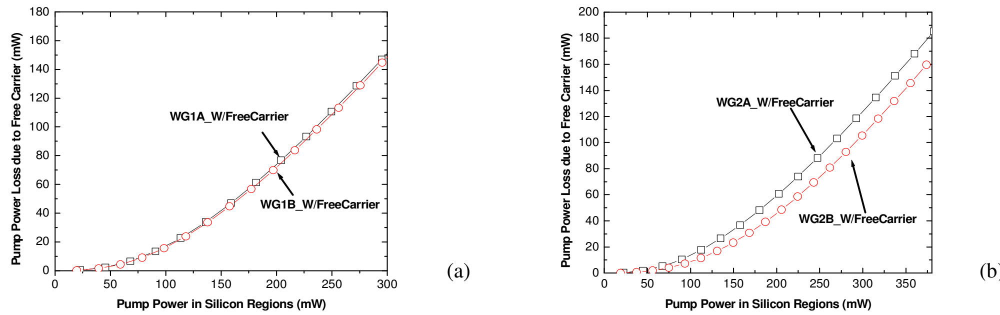

Fig .4. (a) Pump power loss due to free carrier absorption versus pump power in silicon regions for WG1A and WG1B.
(b) Pump power loss due to free carrier absorption versus pump power in silicon regions for WG2A and WG2B.

Signal Gain versus pump power for different geometries is shown in Fig .5 when different linear loss (0 dB/cm, 5 dB/cm, 10 dB/cm) of the system is considered. Overall, muti-trench configurations reduce nonlinear loss both in silicon and erbium; thus, providing up to 0.9dB/cm more signal gain compared to single trench configurations.

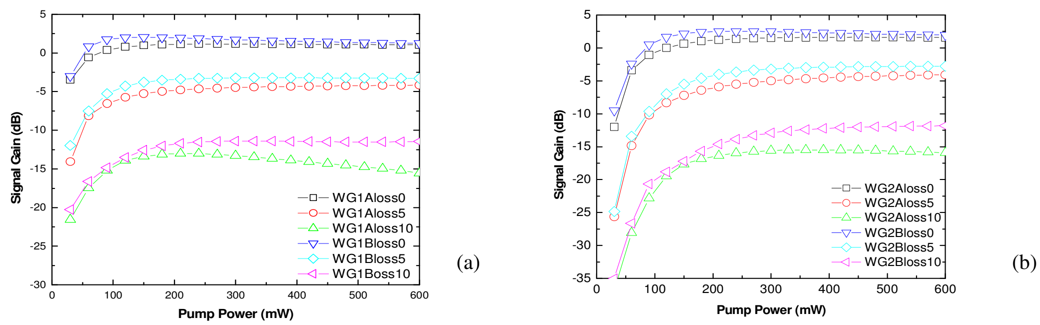

Fig .5. (a) Signal gain versus pump power in silicon regions for WG1A and WG1B for different linear loss.
(b) Signal gain versus pump power in silicon regions for WG2A and WG2B for different linear loss.

5. Conclusion

In conclusion, we have presented graded index silicon waveguide geometries with single and multiple erbium-doped active regions. Distributing gain over larger areas mitigates the effect of nonlinear losses associated with free carriers and erbium-erbium interactions. For instance, multi-trench configurations reduces nonlinear loss in erbium and silicon regions and can generate 0.9dB/cm higher signal amplification with respect to a single trench configuration.

6. References

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