IWA4.pdf

Erbium-Doped Chalcogenide Glass Micro-Disks as Monolithic Mid-IR Laser Sources

Faleh Al Tal[1,*], Clara Dimas[1], Juejun Hu[2,3], Anu Agarwal[2], Lionel C. Kimerling[2]
[1]*Material Science and Engineering, Masdar Institute of Science and Technology, Masdar City, Abu Dhabi, P.O. Box 54224, UAE*
[2]*Microphotonics Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3]*Department of Materials Science & Engineering, University of Delaware, Newark, Delaware 19716, USA*
[*] *corresponding author: falehaltal@IEEE.org*

Abstract: The feasibility of Mid-Infrared (MIR) lasing in Erbium-doped Gallium Lanthanum Sulfide (GLS) micro-disks was investigated. Based on state-of-the-art Chalcogenides micro-disk resonators parameters, lasing was simulated and shown to be possible.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3500) Lasers, erbium; (140.3945) Microcavities

1. Introduction

Chalcogenide glasses (ChGs) are attractive for the development of infrared integrated optical devices for their distinguished mechanical and optical properties [1,2]. Integration of multiple monolithic components on a single substrate enables system-on-chip applications and minimization of size and cost. A basic requirement for such systems is the demonstration of monolithic light sources working in appropriate spectral regimes.

To date, lasing in ChGs has been reported for Nd-doped GLS fiber [3] and laser written waveguides in bulk GLS [4] at 1080 nm, Nd and Tm-doped Tellurite micro-spheres at 1060 nm and 2 µm, respectively [5,6], and most recently Nd-doped GLS micro-sphere at 1080 nm [7]. In addition, theoretical studies showed the possibility of lasing at 4.5 µm and 1.5 µm using Erbium-doped photonic crystals fibers [8]. However, no monolithic ChG laser has been demonstrated or investigated thus far.

MIR photoluminescence was observed for bulk Erbium-doped GLS at 4.5 µm through the transition between $^4I_{9/2}$ and $^4I_{11/2}$ energy levels [9]. Compared to other ChGs, GLS showed the capability of hosting relatively high Erbium concentrations (2.8×10^{20} ions/cm^3) without suffering from luminescence quenching [9]. Nevertheless, because of the small emission cross section of this transition (2.5×10^{-21} cm^2), the maximum possible gain in GLS is limited to less than 4 dB/cm. For lasing to be possible under this gain limitation, resonators with minimum Q factors of 3.5×10^4 are required. Recently, ChG micro-disks with Q factors in excess of 10^5 at 1.55 µm have been demonstrated by a lift-off and subsequent thermal reflow process [10]. This is a key enabler for fabricating monolithic laser sources given the aforementioned specification requirements. The subsequent text discusses the possibility of lasing at 4.5 µm by pumping Erbium-doped GLS micro-disk with 800 nm pump source.

2. Simulation model and results

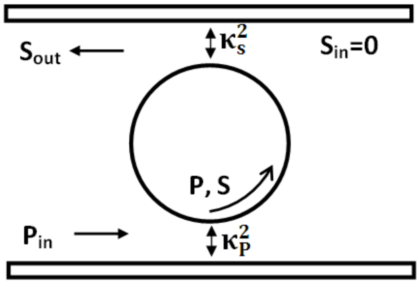

Fig. 1. Laser configuration consists of a micro-disk with input pump waveguide and output signal waveguide. κ^2 is the power coupling coefficient between the bus waveguides and the disk, and P and S stands for the pump and signal, respectively.

The model developed consists of a pump and signal light which are introduced and collected from the disk using separate bus waveguides as illustrated in Fig. 1. The calculations considered: 1) 800 nm pump wavelength and 4.5 µm signal wavelength; 2) refractive indices of 2.42 and 2.35 at the pump and signal wavelengths, respectively were obtained by fitting experimental data [11] to a Cauchy relation; 3) Erbium doping of 2.8×10^{20} cm^{-3}; 4) transverse electric (TE) polarization modes, with dominant electric component parallel to the disk plane, with first order planar index, with single intensity peak in the direction normal to the disk plane, of a disk with 80 µm diameter and 600 nm thickness were included in our calculations; 5) because of the high photon density in the disk, cavity enhancement was ignored; 6) unidirectional propagation was considered and modes splitting effect [12] was neglected.

The solutions of the fundamental signal mode and the pump modes with radial orders, number of intensity peaks in the disk radial direction, up to eight were calculated for the disk cross section in Fig. 2. A large diameter of 80 microns was used to eliminate the signal radiation losses. Having azimuthal symmetry, two-dimensional solution was calculated for the disk cross section along the radial and planar directions. A full-vectorial finite difference mode solver on FIMMWAVE [13] was used.

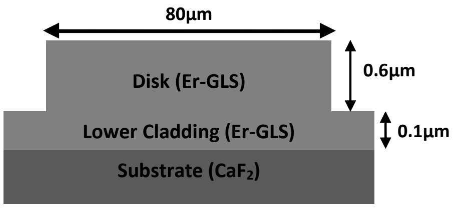

Fig. 2. The micro-disk material cross section showing the CaF$_2$ substrate, Erbium-doped GLS coating layer and disk A CaF$_2$ substrate was used for its low absorption in the MIR regime. As CaF$_2$ can be attacked by moisture, a GLS thin film was taken into account to coat the substrate.

Rosenbrock iterative method was used to solve Erbium rate equations [14]. Using the obtained population distribution of the ions, the signal gain and Erbium absorption of the pump light was computed. The radiation losses were quantified using perfectly matched layer. Volume current formulation [12] was used to estimate the scattering losses for the pump and signal modes based on the roughness parameters of the demonstrated state of the art ChG micro-disk, 10 nm roughness variance and 150 nm roughness correlation length. These coefficients were obtained using preliminary experimental results; more investigations are taking place to enhance the accuracy of these values The bulk absorption coefficient of GLS (0.035 cm^{-1} at 800 nm, and 0.006 cm^{-1} at 4.5 µm) [15] was multiplied by the mode confinement factor to arrive at the modes absorption losses. The calculated Q factors of the pump and signal modes were 1.48×10^4 and 1.53×10^6, respectively. Since the pump modes have small wavelength they suffer from high scattering losses [12], more than 99% of the total losses, and gain very low Q factors. The 7th order pump mode was found to give the highest possible signal gain; hence it was chosen to pump the disk.

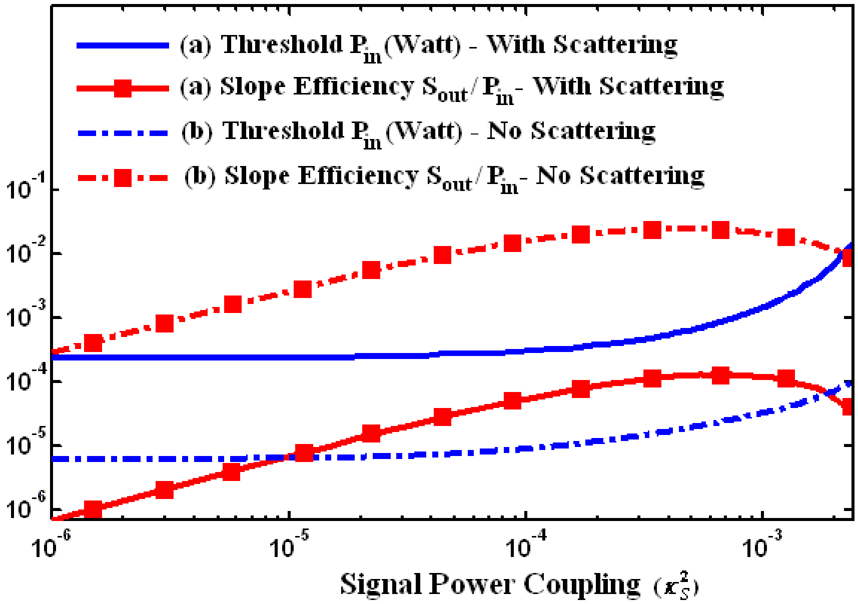

Fig. 3. Threshold pump power and slope efficiency dependence on the signal power coupling. (a) The continuous curve shows the basic case with scattering, for which the maximum slope efficiency is 1.26×10^{-4} with threshold of 0.5 mW and (b) The dashed lines show the performance with no scattering, for this case a maximum efficiency of 2.5% can be achieved with 0.02mW threshold.

The calculated round trip absorption for the pump mode was ~ 75%. Therefore, a pump coupling coefficient (κ_P^2) of 0.25 would maximize the pump power accumulation (P/P$_{in}$) in the disk and minimize the needed input pump power. Using this value for pump coupling, the signal output power was quantified as a function of the pump power and the signal coupling coefficient (κ_S^2) as elaborated in Fig. 3a. The output power peaks at the signal coupling coefficient of 4×10^{-4}. As shown, this value of signal coupling gives an optimized performance for the micro-disk laser as it maximizes the slope efficiency (1.26×10^{-4}) with a lasing threshold of 0.5 mW. Compared to a simulated efficiency of Erbium-doped GaGeSbS fiber [16], which can achieve ~ 15% efficiency, the predicted slope efficiency of the micro-disk is very small. However, fiber lasers require long lengths (tens of centimeters) and do not offer suitable solution for on chip applications. The reason of the low slope efficiency for the micro-disk case is the high scattering losses caused by the sidewalls roughness. Progress is taking place to eliminate these losses [17], for which, as shown in Fig. 3b, two orders of magnitude enhancement is possible.

3. Acknowledgment

The authors gratefully acknowledge contributions from the Electronic Materials (EMat) research group and Michiel Vanhoutte, department of materials science and engineering at Massachusetts Institute of Technology. This study was supported by a grant from Masdar Institute of Science and Technology (Abu Dhabi, UAE).

4. References

[1] B.J. Eggleton, “Chalcogenide photonics: fabrication, devices and applications Introduction,” *Optics Express*, vol. 18, 2010, p. 26632.

[2] A. Zakery, “Optical properties and applications of chalcogenide glasses: a review,” *Journal of Non-Crystalline Solids*, vol. 330, 2003, pp. 1-12.

[3] T. Schweizer, B.N. Samson, R.C. Moore, D.W. Hewak, and D.N. Payne, “Rare-earth doped chalcogenide glass fibre laser,” *Electronics Letters*, vol. 33, 1997, p. 414.

[4] A.K. Mairaj, C. Riziotis, A.M. Chardon, P.G.R. Smith, D.P. Shepherd, and D.W. Hewak, “Development of channel waveguide lasers in Nd 3+-doped chalcogenide (Ga:La:S) glass through photoinduced material modification” *Applied Physics Letters*, vol. 81, 2002, p. 3708.

[5] K. Sasagawa, K. Kusawake, J. Ohta, and M. Nunoshita, “Nd-doped tellurite glass microsphere laser,” *Electronics Letters*, vol. 38, 2002, p. 1355.

[6] J. Wu, S. Jiang, T. Qua, M. Kuwata-Gonokami, and N. Peyphambarian, “2 μm lasing from highly thulium doped tellurite glass microsphere,” *Applied Physics Letters*, vol. 87, 2005, p. 211118.

[7] G.R. Elliott, G.S. Murugan, J.S. Wilkinson, M.N. Zervas, and D.W. Hewak, “Chalcogenide glass microsphere laser,” *Optics Express*, vol. 18, 2010, p. 26720.

[8] F. Prudenzano et al., “Design of Er3+-doped chalcogenide glass laser for MID-IR application,” *Journal of Non-Crystalline Solids*, vol. 355, no. 18-21, pp. 1145-1148, 2009.

[9] T. Schweizer, D. Brady, and D.W. Hewak, “Fabrication and spectroscopy of erbium doped gallium lanthanum sulphide glass fibres for mid-infrared laser applications,” Optics Express, vol. 1, 1997, p. 102.

[10] J. Hu, N. Carlie, N.-N. Feng, L. Petit, A. Agarwal, K. Richardson, and L. Kimerling, “Planar waveguide-coupled, high-index-contrast, high-Q resonators in chalcogenide glass for sensing,” Optics Letters, vol. 33, 2008, p. 2500.

[11] H. Yayama, “Refractive index dispersion of gallium lanthanum sulfide and oxysulfide glasses,” Journal of Non-Crystalline Solids, vol. 239, no. 1-3, pp. 187-191, 1998.

[12] M. Borselli, T.J. Johnson, and O. Painter, “Beyond the Rayleigh scattering limit in high-Q silicon microdisks: theory and experiment,” *Optics Express*, vol. 13, 2005, p. 1515.

[13] FIMMWAVE: Mode solver tool. Photon Design, 34 Leopold Street, Oxford, OX41TW, U.K.

[14] K. Kadono, “Rate equation analysis and energy transfer of Er3+-doped Ga2S3–GeS2–La2S3 glasses,” *Journal of Non-Crystalline Solids*, vol. 331, 2003, pp. 79-90.

[15] Data Sheet: “Gallium Lanthanum Sulphide Optical Material - Internal Transmission”, ChG Southampton Ltd., University of Southampton, Highfield, Southampton, SO17 1BJ, UK., 2010.

[16] M. Desario, L. Mescia, F. Prudenzano, F. Smektala, F. Deseveday, V. Nazabal, J. Troles, and L. Brilland, “Feasibility of Er3+-doped, Ga5Ge20Sb10S65 chalcogenide microstructured optical fiber amplifiers,” *Optics & Laser Technology*, vol. 41, 2009, pp. 99-106.

[17] J. Hu et al., “Optical loss reduction in high-index-contrast chalcogenide glass waveguides via thermal reflow,” Optics Express, vol. 18, no. 2, p. 1469, 2010.