On-chip Integrated Amplifiers and Lasers Utilizing Rare-earth-ion Activation

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This contribution reviews our recent results on rare-earth-ion-doped integrated amplifiers and lasers. We have concentrated our efforts on complex-doped polymers [1], amorphous Al_2O_3 *[2], and crystalline potassium double tungstates [3].*

A polymer host material, based on a cycloaliphatic diepoxy cured with a fluorinated dianhydride, has been developed [4]. When activated with the rare-earth-ion-doped complex, neodymium(thenoyltrifluoroacetone)$_3$ *1,10-phenanthroline, the typical absorption and emission lines of the* Nd^{3+} *ion were detected [4,5,6]. Luminescence quenching, which usually occurs in polymers due to high-energy vibrations from O–H and C–H chemical bonds, was eliminated by the neutral 1,10-phenanthroline ligand and by applying fluorinated chelates to the complex, respectively, and absorption due to the polymer host occurs only in the wavelength range longer than 1100 nm. Optimization of the fabrication procedure of both, host material and optical structure, lead to the first-ever steady-state laser emission from a solid polymer [6]. Continuous-wave (cw) laser operation at 1060.2 nm was demonstrated. The highest slope efficiency was 2.15%, resulting in a maximum output power of 0.98 mW [7]. Lasing was also achieved on the quasi-three-level 878-nm transition. A slope efficiency of 0.35% and an output power of 190* μ*W were obtained [7]. Long-term, stable cw laser operation over at least 2 h was demonstrated.*

Rare-earth-ion-doped Al_2O_3 *planar waveguides were deposited by reactive co-sputtering [8]. Ridge-type channel waveguides with propagation losses as low as 0.2 dB/cm were microstructured into these layers by reactive ion etching [9]. Monolithic integration of these channel waveguides with passive silicon-on-insulator waveguides was demonstrated [10].* $Al_2O_3{:}Er^{3+}$ *integrated optical amplifiers were investigated. For optimum* Er^{3+} *concentrations in the range of 1 to* 2×10^{20} cm^{-3}*, internal net gain was obtained over a wavelength range of 80 nm (1500-1580 nm) and a peak gain of 2.0 dB/cm was measured at 1533 nm [11]. Dopant concentration and gain are limited by a fast spectroscopic quenching process that affects a significant fraction of the* Er^{3+} *ions [12]. Signal transmission experiments were performed at 170 Gbit/s in an integrated* $Al_2O_3{:}Er^{3+}$ *waveguide amplifier. Open eye diagrams and bit-error rates equal to those of the transmission system without the amplifier were observed [13]. A zero-loss power splitter was demonstrated [14]. Optical gain was also investigated in* $Al_2O_3{:}Nd^{3+}$ *at 880 nm, 1060 nm, and 1330 nm [15] and integration of an* $Al_2O_3{:}Nd^{3+}$ *amplifier at 880 nm with an optical backplane was reported [16]. Lasing was obtained for the first time in an* $Al_2O_3{:}Er^{3+}$ *microring resonator [17]. Efficient, ultra-narrow-linewidth channel waveguide lasers in distributed-feedback and distributed-Bragg-reflector configurations [18] were demonstrated in* $Al_2O_3{:}Er^{3+}$ *at 1542 nm [19] and* $Al_2O_3{:}Yb^{3+}$ *at 1022 nm [20], the former with a linewidth of 1.7 kHz, corresponding to a laser Q-factor [21] of* 1.14×10^{11}*, and the latter with a slope efficiency of 67% versus launched pump power and output powers up to 55 mW. The mentioned fast luminescence quenching [12] only increases the threshold of these lasers, but does not affect their slope efficiency [22]. In a dual-wavelength channel waveguide laser in* $Al_2O_3{:}Yb^{3+}$ *whose operation is based on the optical resonances which are induced by two local phase shifts in the distributed-feedback structure, a stable microwave signal at ~15 GHz was created via the heterodyne photodetection of the two laser wavelengths [23].*

High-quality monoclinic $KY(WO_4)_2$ *optical waveguides were grown by liquid-phase epitaxy and laser operation of an* Yb^{3+}*-doped* $KY(WO_4)_2$ *waveguide was demonstrated for the first time. Continuous-wave laser emission near 1 µm was achieved with an output power of 290 mW, and the slope efficiency was above 80% [24]. Co-doping* $KY(WO_4)_2{:}Yb^{3+}$ *layers with optically inert* Lu^{3+} *and* Gd^{3+} *ions allows a large increase of the refractive index contrast with respect to* $KY(WO_4)_2$ *substrates [25]. This paves the way for the realization of integrated optical circuits. Continuous-wave laser operation in a planar waveguide configuration was observed at 1025 nm. A maximum output power of 195 mW was obtained and a slope efficiency of 82.3% was derived, which is the highest value yet reported for a planar waveguide laser to date [26]. In* $KGd_{1-x}Lu_x(WO_4)_2{:}Yb^{3+}$ *channel waveguides grown onto* $KY(WO_4)_2$ *substrates and microstructured by* Ar^+ *beam etching [27], we produced 418 mW of continuous-wave output power at 1023 nm with a slope efficiency of 71% versus launched* *pump power at 981 nm [28]. By grating tuning in an extended cavity and pumping at 930 nm, we demonstrated laser operation from 980 nm to 1045 nm. When pumping at 973 nm, lasing at 980 nm with a record-low quantum defect of 0.7% was achieved [28]. We also fabricated Bragg gratings in such channel waveguides and demonstrated lasing [29]. Furthermore, we exploited the enhanced transition cross-sections, dopant concentrations, and extreme inversion densities attainable in highly* Yb^{3+}*-doped potassium double tungstate channel waveguides, thereby demonstrating a gain of 935 dB* cm^{-1} *in channel-waveguide and 1028 dB* cm^{-1} *in thin-film geometry [30], comparable to the best values reported for semiconductor waveguide amplifiers. This gain is sufficient to compensate propagation losses in plasmonic nanostructures [31], making specific rare-earth-ion-doped materials highly interesting for future nanophotonic devices. Laser experiments were also performed on planar [32] and buried, ridge-type channel waveguides [33] in* ${}_{KY1-x-y}Gd_xLu_y(WO_4)_2:Tm^{3+}$*. With 8at.%* Tm^{3+} *concentration, a slope efficiency of 70% and output powers up to 300 mW around 2* μm *were obtained [34]. Lasing was obtained at various wavelengths between 1810 nm and 2037 nm.*

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