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M.O. Ziegler, M. Hofmann, W. Elsässer and E.O. Göbel (Fachbereich Physik und Zentrum für Materialwissenschaften der Philipps Universität Marburg, Renthof 5, D-35032 Marburg, Germany)

J. Sacher (Joachim Sacher Lasertechnik, Nikolaistraße 9a, D-35037 Marburg, Germany)

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Up-conversion cascade laser at 1.7µm with simultaneous 2.7µm lasing in erbium ZBLAN fibre

C. Ghisler, M. Pollnau, G. Bunea, M. Bunea, W. Lüthy and H.P. Weber

Indexing terms: Fibre lasers, Fluoride glasses, Up-conversion

The authors report on an excited-state-absorption pumped transversally singlemode cascade laser in an erbium ZBLAN fibre. Simultaneous lasing occurred at 1.7µm on the transition $^4S_{3/2} \rightarrow ^4I_{9/2}$ supported by 2.7µm lasing on the transition $^4I_{11/2} \rightarrow ^4I_{13/2}$. The slope efficiency is 1.8% with a threshold of 227mW launched pump power at 791nm.

Introduction: Erbium-doped fluoride fibres are very promising for the construction of compact efficient laser sources and amplifiers for use in telecommunication and for sensors. The 1.7µm transition can be used in applications where eye-safe wavelengths are required, such as terrestrial telemetry on the long edge of the 1.6µm atmospheric window. So far laser action at 1.7µm has been achieved in the pulsed regime by pumping into the $^2H_{11/2}$ level using excitation at 514nm [1]. Pumping around 800 nm, however, would allow the construction of a laser-diode-pumped all-solid-state laser source at 1.7µm.

We report, to our knowledge for the first time, on true continuous-wave up-conversion cascade lasing at 1.7µm supported by 2.7µm lasing in a transversally singlemode erbium ZBLAN fibre. A maximum output power of 4.7mW is achieved at a pump wavelength of 791nm and a pump power of 476mW launched into the core of the fibre.

Experiment: The laser cavity used during the measurements is based on an 82cm-long fluorozirconate fibre (Le Verre Fluoré) doped with 5000ppm mol Er³⁺ ions. The fibre has a core diameter of 6.5µm, NA = 0.156, a cutoff wavelength of 1.3µm and is therefore singlemode at both the 1.7µm and 2.7µm wavelengths. It is CW pumped with an argon-laser-pumped Ti:sapphire laser at 791nm. The overall coupling efficiency into the fibre is 56% of the pump power. This includes the 80% mirror transmission at the pump wavelength of 791nm. The mirrors are butt-coupled to the fibre ends. They were specially manufactured at our Institute to decrease the threshold of the 1.7µm laser transition $^4S_{3/2} \rightarrow ^4I_{9/2}$ and to suppress competitive lasing on the 850 nm transition $^4S_{3/2} \rightarrow ^4I_{13/2}$ [2] which has a large emission cross-section. For this purpose the mirrors have a reflectivity of R = 94% at 1.7µm and a transmission of T = 88% at 850nm. The transmission at 2.7µm is T = 75%. These mirrors are not optimised for maximum output power at 1.7µm.

Fig. 1 Input-output curves for 1.7µm and 2.7µm laser transitions

● 1.7µm
◆ 2.7µm

Results and discussion: We have achieved a transversally single-mode cascade CW laser working at 1.724µm + 1.728µm on the transition $^4S_{3/2} \rightarrow ^4I_{9/2}$ with simultaneous colasing on the transition $^4I_{11/2} \rightarrow ^4I_{13/2}$ at 2.715µm with a threshold of 227mW and slope efficiency of 1.8% for the 1.7µm laser transition. The maximum output power is 4.7mW. The input-output curves for the 1.7µm and 2.7µm lasers are shown in Fig. 1. The 2.7µm laser starts before the 1.7µm laser, but its slope efficiency increases considerably due to the cascade effect when the 1.7µm laser sets on. Because the mirrors on both sides of the fibre are the same, the effective output power and slope efficiency would be about twice the mentioned value. When the mirrors are slightly disaligned the threshold for the 1.7µm line increases and strong lasing at 850nm is observed instead.

An energy-level scheme for Er:ZBLAN fibre is shown in Fig. 2. Pumped with 791nm, the Er³⁺ ions are excited via ground-state absorption (GSA) to the $^4I_{9/2}$ level. The $^4I_{11/2}$ level is then populated via fast multiphonon relaxation. Although the lifetime of the $^4I_{11/2}$ level is smaller than the lifetime of the $^4I_{13/2}$ level, population inversion occurs between the $^4I_{11/2}$ and $^4I_{13/2}$ multiplets due to the large branching ratio $\beta_{20} = 62\%$ into the ground state [3, 4]. Once threshold inversion is reached the 2.7µm transition starts lasing due to a relatively large emission cross-section [5] and the long gain length, although mirror reflectivity at this wavelength is poor. Thanks to the 2.7µm laser the population density of the $^4I_{13/2}$ level substantially increases and the $^2H_{11/2}$ level is efficiently populated by excited-state absorption (ESA) originating from the $^4I_{13/2}$ level [6]. A large proportion of the ions in the $^2H_{11/2}$ level thermally relaxes into the $^4S_{3/2}$ level, from which the transition to $^4I_{9/2}$ is responsible for the 1.7µm laser. The 1.7µm laser populates the $^4I_{9/2}$ level again. As the ESA cross-section has twice the value of the GSA cross-section the cascade laser operates in a closed loop without significant involvement of the ground state, which is heavily bleached [7]. 850nm colasing [8] is suppressed by reducing the

Fig. 2 Energy level scheme of erbium in ZBLAN fibres, indicating GSA $^4I_{15/2} \rightarrow ^4I_{13/2}$, ESA $^4I_{13/2} \rightarrow ^2H_{11/2}$, branching ratios β_{20} and β_{21} for the 970nm and 2.7µm transitions, respectively, laser transitions $^4I_{11/2} \rightarrow ^4I_{13/2}$ at 2.7µm and $^4S_{3/2} \rightarrow ^4I_{9/2}$ at 1.7µm, as well as competitive colasing on the transition $^4S_{3/2} \rightarrow ^4I_{13/2}$ at 850nm

threshold for 1.7µm with a high-reflective mirror of $R = 94\%$ at this wavelength, and by maintaining a high threshold for the 850nm laser due to a transmission of $T = 88\%$. With well aligned mirrors, no colasing at 850nm is observed.

Conclusion: We have achieved a transversally singlemode cascade laser at 1.7µm supported by 2.7µm colasing. The threshold is 227 mW launched pump power at 791nm and the slope efficiency is 1.8%. A maximum output power of 4.7mW from each fibre end is obtained with nonoptimised mirror reflectivities. Based on this cascade principle a diode-pumped all-solid-state compact eye-safe laser can be constructed that operates at the long-wavelength edge within the 1.6µm atmospheric window.

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C. Ghisler, M. Pollnau, G. Bunea, M. Bunea, W. Lüthy and H.P. Weber (Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland)

G. Bunea and M. Bunea: on leave from Institute of Microtechnology-Bucharest, PO Box 36-160, Bucharest-70225, Romania

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High-Q, Ag-doped 123 resonator on unbuffered sapphire substrate

K. Easwar, B.K. Sarkar, D. Kumar, M.S. Hegde, R. Pinto and P.R. Apte

Indexing terms: High-temperature superconductors, Strip line components, Strip line resonators, Resonators, Microwave measurement

The microwave performance of an Ag-doped $YBa_2Cu_3O_{7-x}$ thin-film X-band microstrip resonator on unbuffered sapphire substrate is reported. Q -values of 2400 and 1200 have been obtained at 15K and 77K, respectively, which correspond to R_s values of 330µΩ and 680µΩ.

Introduction: Substrate selection for the realisation of HTSC thin-film-based passive microwave device applications is of crucial importance because the proper choice of substrate determines the film adhesivity, lattice matching and substrate-film reaction. These in turn dictate the T_c , J_c and transport properties of the film. Films with excellent J_c and low microwave surface resistances have been routinely prepared in our laboratories on lattice-matched substrates like $LaAlO_3$ and MgO by a pulsed laser deposition (PLD) technique over a wide range of growth conditions. Yet none of these substrates is as ideally suited for microwave applications as sapphire. Sapphire has an order lower loss tangent compared to most other substrates, good thermal conductivity, high mechanical strength and low cost.

However, efforts to grow high T_c films on sapphire have not met with the desired success globally since sapphire reacts with $YBa_2Cu_3O_{7-x}$ at the temperature required to form a good superconducting phase. This poses difficulty for obtaining high T_c and J_c for HTSC films on sapphire. A suitable buffer layer, lattice-matched with both sapphire and YBCO and chemically stable up to the processing temperature of YBCO thin-film deposition, like yttria-stabilised zirconia [1] or $SrTiO_3$ [2], improves the in-plane epitaxy of YBCO on sapphire. Work has also been reported [3] on the deposition of YBCO on bare sapphire at low deposition temperatures where sapphire does not seriously react with the 123 film, but this effort has yielded poor transport properties.

In this background we have tried the deposition of Ag-doped YBCO on sapphire to improve the transport properties and microwave performance. The benefits of doping YBCO thin films with Ag [4] have already been reported. For sapphire, over and above these benefits, Ag-doping offers lower temperature of deposition, which is the most crucial parameter in determining the extent of chemical reaction between YBCO and sapphire [5]. The novelty of our results lies in achieving deposition at relatively low temperatures (700°C) and yet realising good quality YBCO films with the aid of Ag doping.

Device design and fabrication: The microwave characterisation was carried out on an X-band, half-wavelength, capacitive gap coupled microstrip resonator with a single side YBCO film. The film was grown *in situ* by the PLD technique with a laser spot size of 3.5mm × 1mm, a target-substrate distance of 4.5cm and oxygen pressure of 300mtorr, and was subsequently cooled at 500torr oxygen in the growth chamber itself. The YBCO target had an Ag doping of 10wt%. The film thickness was 4000Å. The microstrip resonator was patterned using photolithography and wet etching with 1% phosphoric acid acting as the etchant.