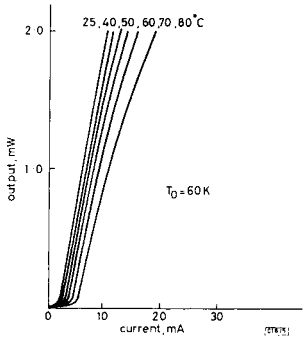

Fig. 5 *Temperature dependence of light output*

Device length: 120µm

These measured characteristics demonstrates the potential of the proposed EXSAS-LDs in forming low threshold laser arrays. The laser structure has not yet been fully optimised, however, excellent characteristics have been already achieved.

Conclusion: A new type of low-threshold laser array, the EXSAS-LD array, which has submicrometre-wide bulk active stripes, was proposed and fabricated by selective MOVPE. A uniform 17channel array with average threshold of 3.5mA was demonstrated.

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S. Kitamura, T. Sasaki, K. Komatsu and M. Kitamura (*Opto-Electronics Research Labs., NEC Corporation 34 Miyukiga-oka, Tsukuba, Ibaraki 305, Japan*)

References

1 GOODMAN, J.W., LEONBERGER, F.J., KUNG, S.Y., and ATHALE, R.A.: 'Optical interconnections for VLSI systems', *Proc. IEEE*, 1984, **72**, pp. 850–866
2 OISHI, A., OKA, A., KAWANO, T., ONO, Y., UOMI, K., TSUCHIYA, T., KOMORI, M., and TAKAI, A.: 'Low-threshold (1.8mA) and high-efficiency (0.39W/A) 1.3-µm strained quantum well 10-element laser arrays for high-throughput optical interconnections'. ECOC '93 Tech. Dig., 1993, Paper ThC12.6, Vol. 3, pp. 21–24
3 SASAKI, T., and MITO, I.: 'Selective MOVPE growth for photonic integration circuits'. OFC/IOOC '93 Tech. Fig., 1993, Paper ThK1, pp. 210–212
4 KITAMURA, S., KOMATSU, K., and KITAMURA, M.: 'Polarization-insensitive semiconductor optical amplifier array grown by selective MOVPE', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 173–175

High-accuracy measurement of the linewidth of a Brillouin fibre ring laser

J. Boschung, L. Thévenaz and P.A. Robert

Indexing terms: Stimulated Brillouin scattering, Fibre lasers, Ring lasers, Laser linewidth, Laser variables measurement

A high resolution spectral analysis of the emission of a stimulated Brillouin scattering fibre ring laser has been performed, demonstrating the single frequency operation of such lasers and a 3Hz emission linewidth.

Introduction: Increasing interest in stimulated Brillouin scattering (SBS) in optical fibres has led to great efforts to develop SBS fibre ring lasers and study their spectral properties [1]. Promising applications in the field of optical fibre laser gyros [2] and tunable microwave beat signal generation [4] have been reported. Stimulated Brillouin scattering (SBS) is a nonlinear inelastic process that occurs in optical fibres at a much lower pump power than most other nonlinear effects. It leads to amplification of a backward-propagating Stokes wave shifted in frequency by $\nu_B = 2nV_a/\lambda$, where V_a is the acoustic velocity within the fibre, n is the refractive index and λ the wavelength of the incident lightwave. Laser emission using SBS can be achieved in an all singlemode fibre resonators and the low round-trip loss leads to a threshold pump power in the submilliwatt range [4]. The generated Stokes wave is expected to be highly coherent and a 30Hz linewidth has been reported [3]. Nevertheless true single frequency operation has not been clearly shown to date.

In this Letter we demonstrate single-frequency operation of a Brillouin fibre ring laser, even though many cavity modes lie under the Brillouin gain curve and may thus potentially give rise to laser emission. The free-running linewidth of this laser was measured in the Hertz range. This is to our knowledge the most accurate measurement performed to date on such lasers.

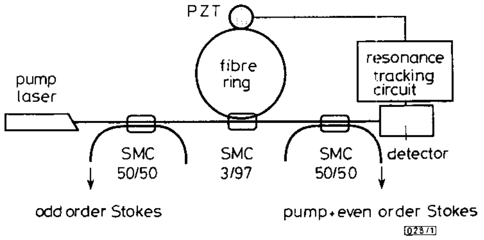

Fig. 1 *Experimental setup of stimulated Brillouin scattering fibre ring laser*

PZT: piezoelectric fibre stretcher, SMC: singlemode fibre coupler with splitting ratio

Laser description: The SBS laser ring resonator is made of a 28 m standard singlemode fibre (9µm core diameter) spliced to a singlemode coupler with a 3% coupling ratio, as shown in Fig. 1. The resonator free spectral range (FSR) is 6.9MHz with a finesse of 80. The pump laser is a 1319nm single frequency Nd:YAG laser with a 100kHz linewidth. The fibre ring resonator length is tuned using a PZT stretcher, so that it is kept in resonance with the pump laser light. The threshold for SBS emission is reached for a 0.4mW pump power in the resonator input fibre and a laser line is observed 12.8GHz below the pump laser frequency. The maximum power launched into this fibre exceeds 10mW, so that the generation of successive Stokes waves is possible up to the fourth order, a sufficiently intense Stokes wave pumping the next order Stokes wave above threshold. Even order Stokes waves are copropagating with the Nd:YAG pump light in the resonator, while odd order waves are contrapropagating, so that even and odd order Stokes waves have a distinct output fibre.

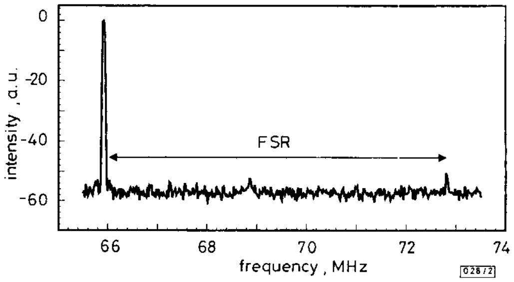

Fig. 2 *Beat signal between first Stokes wave and tunable Nd:YAG laser, showing SBS laser sidemode amplitude*

Sidemode measurement: The single frequency operation of the SBS laser was first checked. This was achieved using a second Nd:YAG laser, tunable over more than 30GHz, so that its light can beat with the SBS laser output, as shown in Fig. 2. The different frequency components are each separated by one FSR. The major peak corresponds to the beat note between the tunable

Nd:YAG and the SBS laser lines. Sidemode beats are 50dB below, corresponding to a nearly 100dB intensity sidemode suppression ratio.

Linewidth measurement: The measurement shown in Fig. 2 provides no information about the coherence of the SBS emission, because the 100kHz linewidth of the tunable Nd:YAG laser is much larger than the expected Stokes linewidth. This information was obtained by analysing the beat note between two Stokes waves of different order, because they are uncorrelated and their linewidths are equally narrow. The major issue is the 12–13GHz beat frequency, making difficult a highly accurate linewidth measurement with affordable instrumentation. However this beat frequency can be arbitrarily decreased by optically modulating one of the Stokes waves, so that one of the modulation sidebands is close in the optical spectrum to the other Stokes wave. This was achieved using a guided-wave electro-optic intensity modulator with a bandwidth in excess of 12GHz.

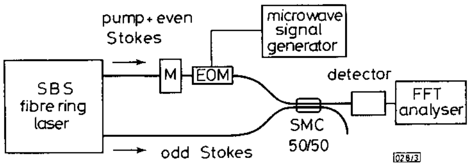

Fig. 3 *Experimental setup used to measure linewidth of SBS laser shown in Fig. 1*

M: monochromator, EOM: guided-wave electro-optical modulator, SMC: singlemode fibre coupler

Fig. 3 shows the experimental setup used to measure the SBS laser linewidth. The power of the pump YAG laser is set, so that the second Stokes wave is above threshold. The remaining pump light is entirely filtered out from the copropagating second Stokes wave using a monochromator with a 0.1nm resolution, because their frequency difference $2\nu_B \simeq 25$GHz corresponds to a 0.17nm wavelength difference at 1319nm. The filtered light is then modulated using the intensity modulator driven by a microwave signal generator. The frequency of the generator is set close to ν_B, so that the frequency difference between the upper sideband of the modulated second Stokes wave and the first Stokes wave is below 100kHz. The resulting beat signal therefore lies in the low frequency range and can be analysed with an arbitrary resolution using an FFT analyser.

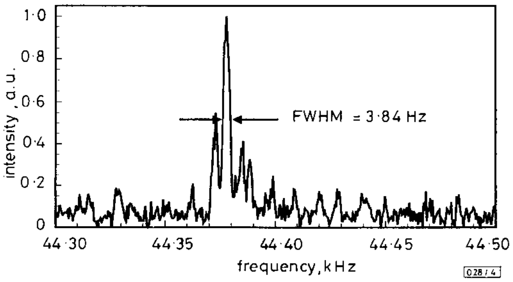

Fig. 4 *Spectrum of beat note between first Stokes wave and upper sideband of modulated second Stokes wave*

The multiple peak pattern is due to the optical line drift during the 2s measuring time

Results: Fig. 4 shows the spectrum of the beat signal between the first Stokes and the upper sideband of the modulated second Stokes. The 3Hz linewidth is five orders of magnitude narrower than the pump laser linewidth. A slow 200Hz drift of the beat signal is observed in a minute time scale, due to fluctuations of the pump laser frequency ν_0. This corresponds to a 3.5MHz pump frequency drift, according to the scaling relation $\delta\nu_{Beat}/\nu_B = \delta\nu_0/\nu_0$, where ν_B is the Brillouin Stokes shift. This drift prevents us from measuring the ultimate Brillouin linewidth that should lie in the subhertz region.

By increasing the pump power even further, the threshold of the third Stokes wave is reached, and the lower sideband of the modulated second Stokes can beat with the third Stokes, as shown in Fig. 5. The two beat frequencies are not identical owing to the fibre chromatic dispersion that changes the cavity optical length. However an 800Hz beat frequency difference was expected from calculations, which is much less than the 1.8kHz experimental value. This discrepancy can be explained by either an enhanced dispersion in the coupler, or the presence of the Kerr effect [5] and mode pulling [6] in the cavity.

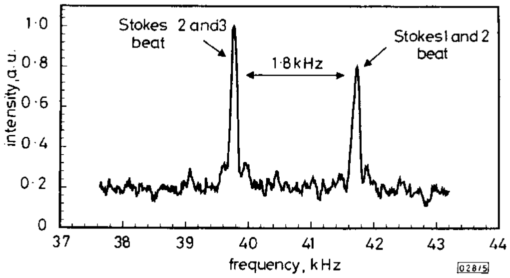

Fig. 5 *Beat signals between first Stokes and upper sideband of modulated second Stokes, and between third Stokes and lower sideband of modulated second Stokes, showing chromatic dispersion effect*

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J. Boschung, L. Thévenaz and P. A. Robert (*EPFL Swiss Federal Institute of Technology Metrology Laboratory CH-1015 Lausanne, Switzerland*)

References

1 STOKES, L.F., CHODOROW, M., and SHAW, H.J.: 'All-fibre stimulated ring laser with submilliwatt pump threshold', *Opt. Lett.*, 1982, **7**, pp. 509–511

2 ZARINETCHI, F., SMITH, S.P., and EZEKIEL, S.: 'Stimulated Brillouin fibre-optic laser gyroscope', *Opt. Lett.*, 1991, **16**, pp. 229–231

3 SMITH, S.P., ZARINETCHI, F., and EZEKIEL, S.: 'Narrow-linewidth stimulated Brillouin fibre ring laser and applications', *Opt. Lett.*, 1991, **16**, pp. 393–395

4 KALLI, K., CULVERHOUSE, D.O., and JACKSON, D.A.: 'Fiber frequency shifter based on generation of stimulated Brillouin scattering in high-finesse ring resonators', *Opt. Lett.*, 1991, **16**, pp. 1538–1540

5 HUANG, S., THEVENAZ, L., TOYAMA, K., KIM, B.Y., and SHAW, H.J.: 'Optical Kerr-effect in fiber-optic Brillouin ring laser gyroscopes', *IEEE Photonics Technol. Lett.*, 1993, **5**, pp. 365–367

6 NICATI, P.A., TOYAMA, K., HUANG, S., and SHAW, H.J.: 'Frequency pulling in a Brillouin fiber ring laser', *IEEE Photonics Technol. Lett.*, July 1994, **6**

Optical sampling using nondegenerate four-wave mixing in a semiconductor laser amplifier

M. Jinno, J.B. Schlager and D.L. Franzen

Indexing terms: High-speed optical techniques, Multiwave mixing, Semiconductor optical amplifiers

Picosecond optical sampling using nondegenerate four-wave mixing in a semiconductor laser amplifier (SLA) is demonstrated for the first time. High-peak-power pulses and electrical gating of the SLA produce an optical sampling signal with a high signal-to-noise ratio.