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Generation of micro- and THz-waves at 1.5 μm by dual-frequency Er:Yb laser

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A promising technique for generating discrete-tunable beat-note signals is presented and investigated. Two tunable fibre gratings provide external feedback to an Er:Yb laser. Beat-notes from 60 GHz up to ~2 THz are achieved. Power equalisation is discussed and the partition noise is measured.

Introduction: Delivery of microwave signals on optical carriers is a promising evolution of microwave networks [1]. In addition, sources of high-frequency signals (hundreds of gigahertz up to several terahertz) are interesting for many applications from far infrared spectroscopy [2] to optical communications [3]. An effective technique to generate microwave and THz-signals is to use the beat-note of two continuous wavelength signals generated from a dual wavelength laser source. Several dual-wavelength laser sources have been proposed so far, both semiconductor lasers [4, 5] and bulk lasers with separated intracavity-beam paths [6].

In this Letter we describe a straightforward and promising alternative technique for generating microwave and THz signals based on a compound cavity formed by a standard multi-wavelength laser cavity with external feedback provided by two fibre Bragg gratings (FBG). This source joins the high-temporal coherence of a solid-state laser with the simplicity of FBG tuning. We also investigate the properties and limitation of such approach.

Laser setup: Fig. 1 shows the dual-frequency laser cavity setup. The laser source is a double cavity consisting of a main cavity (dashed box in Fig. 1) and two external FBGs. The main cavity is a standard diode-pumped bulk Er:Yb:phosphate glass laser [7] consisting of two elements: a 1 mm thick plano-plano Er:Yb glass rod and a 10 mm radius of curvature 98% reflectivity output coupler. The main cavity is therefore a multi-wavelength oscillator with high-finesse and high-free spectral range (FSR ~15–30 GHz); the free running wavelengths are all at around the erbium gain peak at ~1533 nm. The main difference with respect to previous reported cavities is the pumping system. To reduce the size of the laser device, we used only a single GRIN lens (dot pitch 0.28) to focus the radiation emitted by a broad area (1 × 100 μm²) InGaAs laser diode. However the GRIN lens cannot compensate for the strong ellipticity of the pump laser diode and the maximum pump power was limited by thermal effects to a value of ~300 mW. Note that the ytterbium concentration was similar to [7] and a QX glass base (Kigre Inc.) has been used to reduce thermal stress. The maximum output power was ~45 mW at 1533 nm with 70 mW pump power threshold in multimode operation. The output coupler was glued to a piezoelectric transducer (PZT) for fine tuning of the main cavity FSR. The output beam from the main cavity was focused into a singlemode fibre by suitable optics with efficiency greater than 80%.

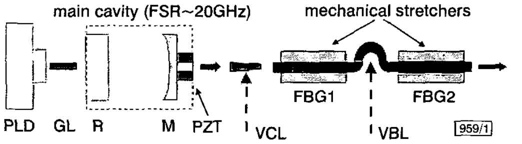

Fig. 1 *Schematic diagram of laser cavity*

PLD: pump laser diode; GL: grin lens; R: laser rod; M: $R = 98\%$ mirror; PZT: piezoelectric transducer; LS: lens system; VBL: variable (macro)bending losses; VCL: variable coupling losses

To achieve dual-frequency operation we used external feedback provided by two cascaded FBG gratings as shown in Fig. 1. The FBG peak wavelengths define the two oscillating wavelengths provided that their reflectivity is properly chosen. In our experimental setup, unless otherwise stated, we used two 1550.4 nm centre wavelength FBGs acting as output coupler of the compound cavity. The FBGs full-width half maximum (FWHM) was ~33 GHz and the reflectivity was 80% and 90% for FBG1 and FBG2, respectively, the FBG2 reflectivity being larger to compensate for the extra splicing fibre loss. In this configuration we observed that the free-running lasing at 1533 nm was suppressed in favour of lasing at the FGB centre wavelength (1550.4 nm) when ~50% of the main cavity output power was coupled into the fibre.

A mechanical stretcher was able to provide up to ~3 nm tuning for gratings. The beat-note tuning was carried out by mechanical stretching of the FBG and optimised by matching the main cavity FSR to the new FBG peaks by finetuning the PZT. The advantage of the present system, compared to other dual-wavelength bulk lasers with independent intracavity beam paths, is that the main cavity never needs realigning and therefore the tuning process is very reliable despite the limitation arising from the need to match both FBGs' peaks and main cavity FSR. The linewidth of each mode was below 10 kHz and the relative short-term mode-spacing stability ($\Delta\nu/\nu$) was better than 10^{-7}.

The main issue for dual-frequency lasers is power equalisation in order to avoid a bias continuous-wave signal superimposed to the beat-note. We achieve power equalisation by using two different techniques depending on the frequency separation. If the frequencies are close (< a few hundred gigahertz) we introduced extra loss in the second FBG cavity by, for example, tuning the fibre macrobending loss. When the frequencies are far apart (> ~8 nm, i.e. they operate on different Stark transitions) finetuning of the common cavity loss by changing the main cavity to fibre coupling efficiency is able to equalise the power of the two wavelengths [8].

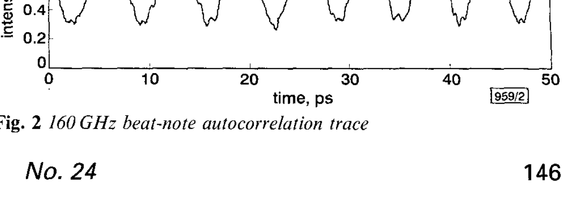

Fig. 2 *160 GHz beat-note autocorrelation trace*

Experiments: We performed several experiments to generate beat-notes for applications ranging from high-speed communications (160GHz) and microwave network (60GHz) to THz waves. In the first set of experiments we fixed the main cavity FSR at 20GHz (~7.5mm bulk cavity optical length) by carefully tuning the PZT voltage. We tuned apart the two FBGs in 20GHz steps from 40 to 200GHz by stretching FBG1. Fig. 2 shows an example of the autocorrelation trace of a ~160GHz beat-note signal, i.e. when the two FBGs were tuned apart by about eight times the main cavity FSR. A clean 60GHz beat-note was also achieved.

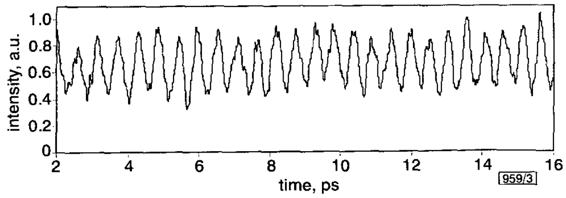

Fig. 3 *1.99 THz beat-note autocorrelation trace*

To increase the beat-note frequency to the THz range we performed a second set of experiments where we used a 1533.6nm peak wavelength FBG as FBG2. We obtained a beat-note up to ~2.1THz by using two FBGS centred at 1533.6 and 1550.4nm. A 1.99THz beat-note is shown in Fig. 3. The unresolved signal is due both to the limitation of our measurement setup and to the penalty discussed next.

The main issue of such a multi-wavelength approach is the intrinsic penalty due to partition noise. The problem can be detrimental because the antiphase dynamic generates an oscillating bias superimposed to the beat-note signal. To evaluate the partition noise we measured the relative-intensity-noise (RIN) of the laser by feeding a low noise photodiode. The electrical signal was recorded by a high-resolution electrical spectrum analyser (HP mod.3588). Measurements refer to the conditions of Fig. 3.

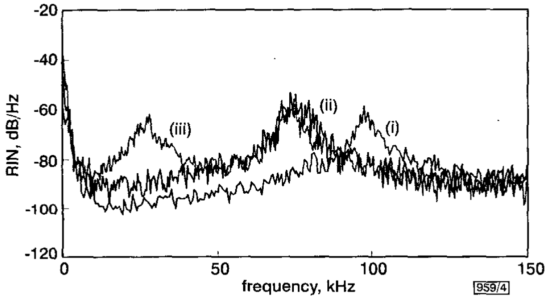

Fig. 4 *RIN spectra*

(i) single-frequency operation at 1534nm
(ii) dual-frequency operation - total power
(iii) dual-frequency operation - power at 1534nm

Fig. 4 shows the RIN spectra for three different conditions. Curve (i) shows the RIN spectrum of the laser operating in single-frequency operation at 1534nm (FBG1 was absent). Curve (ii) shows the RIN spectrum of the total output power when dual-frequency operation at 1534nm and at 1550nm is obtained. Curve (iii) in Fig. 4 shows the RIN spectrum of the 1534nm wavelength mode observed after filtering out the 1550nm power by a tunable filter (Santec mod. TDS-820, ~133GHz FWHM) centred at 1534nm. From Fig. 4 it is apparent that RIN at around the relaxation oscillation frequency is unchanged but a large low frequency RIN peak is found. The extra noise is due to competition between the two lasing wavelengths and it can be seen, by observing curve (ii) in Fig. 4 where the total power does not exhibit the same feature, that the two modes behave in antiphase (when mode 1 has maximum power mode 2 has minimum power). In our case the antiphase dynamics superimpose on the sinusoidal beat-note a bias oscillating at ~27kHz frequency. We believe the partition noise can be reduced by improving the mechanical stability of the main cavity to fibre focusing optics as well as by reducing the length of the fibres. The high RIN peak value, compared to other devices [7], is due to the limited pump power and to back reflections to the pump lasers that increase the laser diode RIN. An improved cavity design will be able to reduce the whole RIN spectrum.

Conclusions: We have proposed a simple cavity design to generate beat-note signals in the mm- to THz-frequency range. We have demonstrated that optical feedback from external cavity FBGs provide for reliable and discretely tunable beat-note signals. The antiphase dynamic noise induced by the dual-frequency operation has been investigated and it represents the main limitation of such a source for critical applications.

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Optically transparent frequency selective window for microwave applications

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The microwave behaviour of a frequency selective window consisting of a cascade of two optically transparent band-stop frequency selective surfaces (FSSs) made with highly conductive, highly transparent thin-film indium tin oxide (ITO) is investigated. The performance of the ITO FSS structure is compared to a similar structure made from copper. Experimental results demonstrate the improved band-stop behaviour of a double layer window over a single layer one.

Introduction: An optically transparent frequency selective surface (FSS) made from a transparent conductor can be favoured more than a metal-based opaque FSS whenever the continuity of the optical field of view through the FSS is required. This is true in applications where aesthetic presentation can be important for its