Dual-Frequency VECSEL at Telecom Wavelength for Sensing Applications

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Abstract: We aim at realizing an optically-pumped, dual-frequency VECSEL at telecom wavelength (1.5 µm) with a frequency difference in the radio-frequency (RF) range (around 11 GHz), to be used in a sensor unit based on Brillouin scattering in optical fibers. Laser emission of two orthogonally-polarized cavity modes with a controlled frequency difference is obtained by inserting a birefringent crystal in the VECSEL cavity. We have examined the influence of the different intra-cavity elements on the laser emission. It is shown that optimizing the free spectral range and the bandwidth of the intra-cavity Fabry-Perot etalon is of practical importance to achieve a stable single longitudinal laser emission for each of the two orthogonal polarizations. The optimization of the output power has also been investigated and it is concluded that up to 100 mW output power can be expected by adjusting the reflectivity of the output coupling mirror of the VECSEL cavity. The achievement of a highly-stable frequency difference is crucial for sensing applications. For this reason the influence of different parameters on the stability of the dual-frequency emission have been studied. It is concluded that mechanical vibrations are the main cause of the RF signal instability in our free-running VECSEL cavity. The design of a compact or mono-block cavity may allow to meet the stability requirements for our sensors.

1 INTRODUCTION

For over two decades, distributed optical fiber sensors based on Brillouin scattering have gained significant interest for their ability to monitor temperature and strain in large infrastructures. When an incident light interacts with acoustic phonons propagating in the fiber core, Brillouin scattered light is generated. The Brillouin frequency depends on temperature and/or strain variation in the optical fiber. Sensing techniques are based either on Brillouin spontaneous scattering (Zou, et al., 2015) or on Brillouin stimulated scattering (Brown, et al., 1999). In both cases the signal detection is achieved in the high frequency domain, e.g. at the scattered Brillouin frequency, υ_B ~11GHz in single-mode standard fibers (SMF), where the electronic devices used for the detection and analysis of the signal are expensive. A solution was proposed by Geng *et al.* to realize the signal detection and analysis at a lower frequency, helping to get rid of these expensive and cumbersome electronic devices (Geng, et al., 2007). This solution consists in using a Brillouin fiber laser pumped by a fiber laser source. A part of the incident light emitted from the fiber laser is injected in the fiber under test, while another part of this incident signal is used to pump the Brillouin laser which acts as a local oscillator and has a frequency difference with the incident laser close to 11 GHz. The signal detection is realized at the frequency (ν_1-ν_B), where ν_1 is the beat frequency of the local oscillator. This is a good solution to reduce the cost of the detection system, but the synchronization of the two fiber laser sources is rather complex wich will raise the cost of the sensor unit.

Based on this idea we suggest the use of a dual-frequency VECSEL, where the two frequencies (the frequency used to pump the fiber under test and the frequency of the local oscillator) share the same cavity. A stable frequency difference could be

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expected in such a configuration, and costly electronics to synchronize the two frequencies may be avoided. The on-going work for the realization of a dual-frequency VECSEL emitting at 1.5 µm is presented in the following.

2 EXPERIMENTAL RESULTS

2.1 Overview of Dual-Frequency Lasers at 1550Nm

Before 2009, dual-frequency micro-lasers were based on diode-pumped solid-state lasers, e.g., Nd:YAG, Yb,Er:Glass and Yb:KGW (Alouini, et al., 1998) (Brunel, et al., 1997) lasers. An electro-optic modulator was used for frequency separation and a Fabry- Perot (F-P) etalon was used to ensure a single longitudinal mode operation on each polarization. A dual-frequency vertical extended cavity surface emitting laser (VECSEL), emitting at 1µm, was first reported by Baili *et al.* (Baili, et al., 2009), to benefit from the class A operation of this semiconductor disk laser, which is free from relaxation oscillations. The cavity concept was the same as for the dual-frequency crystal-doped solid state lasers. A F-P etalon was inserted in the extended cavity to select a single-longitudinal cavity mode, and a birefringent crystal (YVO_4) was used to ensure a frequency separation between the two orthogonal polarizations. In this first report, the VECSEL chip was grown on a GaAs substrate. The bottom highly-reflective mirror, a distributed Bragg reflector (DBR), consisted of alternating GaAs and AlGaAs quarter-wavelength layers, and the active region consisted of InGaAs/GaAs quantum wells to emit around 1µm. Based on this idea, in 2012 F.A. Camargo *et al.* have demonstrated the first dual-frequency VECSEL operating at 852nm dedicated to the coherent population trapping of Cesium atoms (F.A.Camargo, et al., 2012). The cavity principle was the same (a birefringent crystal and a Fabry-Perot etalon were used), but this time the VECSEL active region was composed of GaAs quantum wells, embedded in AlGaAs barriers and pump-absorbing layers. In 2014, De *et al.* (De, et al., 2014) reported the first dual-frequency VECSEL emitting at 1550nm using the same cavity configuration. The VECSEL chip was grown on an InP substrate and InGaAlAs multi quantum-wells were used as the active region. Our aim is to realize a dual-frequency VECSEL emitting at 1550nm with a frequency difference of ~ 11GHz, close to the scattered Brillouin frequency in SMF. As the Brillouin sensors use optical fibers, it is interesting to use a laser source operating at 1550nm where the optical attenuation is minimum. In order to integrate this source into a Brillouin fiber sensor some specifications have to be met:

- Laser output power typically lower than 10mW for spontaneous Brillouin sensors
- Laser output power of a hundred of mW, for stimulated Brillouin sensors
- RF linewidth of the beat note < 0.5MHz, with a temporal jitter/drift typically <0.5 MHz over several minutes to allow the detection of ~0.5°C temperature variation (Shimizu et al., 1992).

The realization of the 1.5µm dual-frequency laser source is detailed in the following. The achieved results are presented and compared to the targeted specifications.

2.2 VESCEL Chip Fabrication

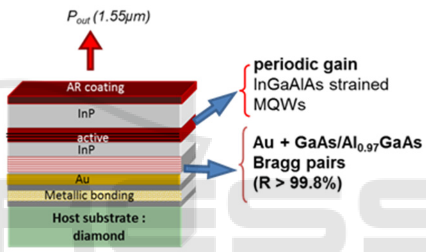

Figure 1: VECSEL chip emitting at 1550nm.

The completed VECSEL structure is schematically depicted in Figure 1. The VECSEL chip is similar to that used for the fabrication of the first dual-frequency VECSEL at 1550nm (De, et al., 2014). Briefly the active region is grown on an InP substrate. It is designed for optical pumping at 980nm and includes strained InGaAlAs quantum wells. A 17-pair $GaAs/Al_{0.97}Ga_{0.03}As$ DBR is integrated to the active region using a metamoprhic regrowth (Tourrenc, et al.,2008). A gold layer is deposited on the surface of the Bragg mirror to enhance its reflectivity. The semiconductor chip with deposited gold is then integrated to a CVD diamond host substrate using metallic bonding. The InP substrate, and the etch-stop layer are then removed using selective chemical etching. Finally the InP top layer of the VECSEL may be finely etched to tune the resonance wavelength of the microcavity close to 1550nm, and an anti-reflective (AR) coating at 980 nm is deposited on the surface to enhance pump absorption (Zhao, et al., 2012).

2.3 VECSEL Cavity Configuration for Dual-Frequency Emission

The fabricated VECSEL chip was first qualified in a simple plane-concave cavity, as depicted in Figure 2.

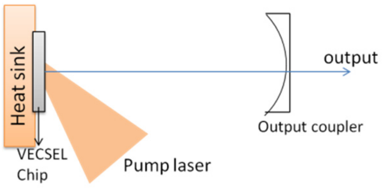

Figure 2: Simple VECSEL cavity.

The VECSEL is assembled with a highly-reflective concave mirror (output coupler) to form a stable plane-concave cavity. The VECSEL chip is pumped by a 980-nm laser diode at 45° incidence. The VECSEL output power versus pump power (L-P curve) obtained with the concave mirror used in the dual-frequency experiments, and having a reflectivity of 99.7% is reported in Figure 3.

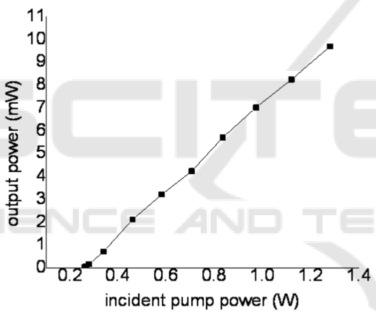

Figure 3: Output power obtained in the simple cavity of Fig. 2. The cavity length is of 8.8mm, the concave mirror has a radius of curvature of 10mm (leading to a cavity mode radius equal to ω_0=40µm).

To realize the dual-frequency laser operation a birefringent crystal plate (YVO_4) cut at 45° of the optical axis is inserted in the extended cavity. The plate is AR-coated at 1550nm on both faces. This type of birefringent crystal leads to both a frequency separation and a spatial separation (s) of the two orthogonally-polarized longitudinal cavity modes. For a plate thickness of 500 µm, s=50µm. An intra-cavity F-P etalon allows to select only one longitudinal mode for each of the two polarizations. In our experiment a glass (SiO_2) etalon with a thickness of 160µm (free spectral range FSR=5nm) has been used. The cavity scheme is depicted in Figure 4. The cavity length was fixed at ~ 8.8mm in order to maintain a cavity free spectral range larger than 11GHz.

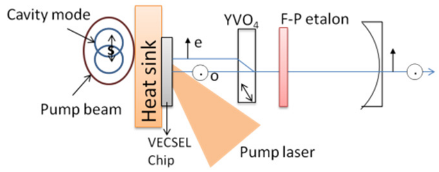

Figure 4: Schematic of the dual-frequency VECSEL cavity. On the left: schematics of the spatially-separated cavity modes (blue) and pump spot (brown).

After the insertion of the YVO_4 crystal, and fine tuning of both, the pump position and output coupler position, simultaneous and robust oscillation of the two orthogonally-polarized eigenstates is achieved, as illustrated in Figure 5. The optical pumping system has been designed to create an elliptical pumping spot with an adapted size to pump uniformly the two spatially-separated cavity modes at the VECSEL chip surface.

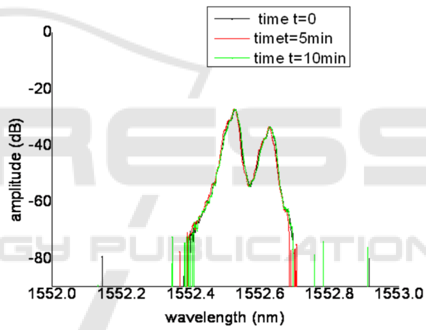

Figure 5: Optical spectrum of the dual-frequency laser emission. Cavity length~8.8mm, YVO_4 (500-µm thick), SiO_2 Fabry-Perot etalon (thickness of 160µm).

2.4 Results

2.4.1 Influence of the Intra-Cavity Elements and Output Coupling Mirror on the Output Power

We have measured the VECSEL output power versus incident pump power (L-P curve) in dual-frequency operation. After the insertion of the intra-cavity elements the output power was typically reduced to half, as illustrated in Figure 6. The maximum output power may be sufficient for a sensing unit based on spontaneous Brillouin scattering, but is not sufficient for stimulated Brillouin scattering.

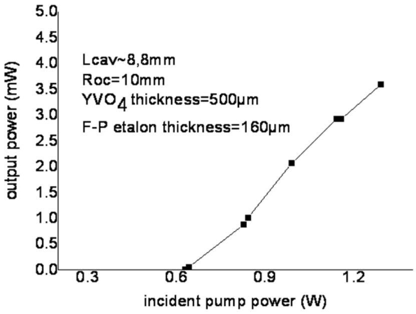

Figure 6: Dual-frequency laser output power versus pump power using an output coupler of reflectivity 99.7%.

We have therefore examined the influence of the cavity elements on the cavity losses and laser efficiency.

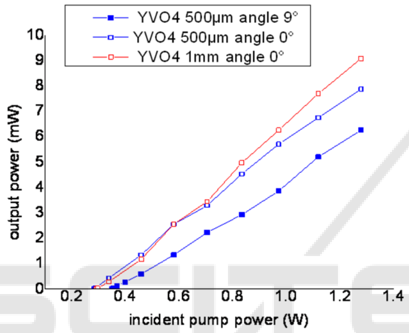

Figure 7: VECSEL L-P curve with a 500-µm, and a 1-mm thick YVO_4 plate at normal incidence in the cavity, and with a 500-µm thick YVO_4 plate rotated by 9° in the cavity (the output coupler reflectivity is 99.7%).

Figure 7 shows the VECSEL L-P curve with YVO_4 plates of different thicknesses and different orientations in the cavity. A 0° incidence means that the plate is normal to the cavity axis. Two conclusions can be made by examining the figure. Firstly, the thickness of the YVO_4 plate doesn't have any significant impact on the output power, and this birefringent crystal is therefore well adapted to the wavelength of 1550nm. Secondly a slight rotation of the birefringent crystal (by 9° in the Figure 7) in the cavity doesn't affect significantly the output power.

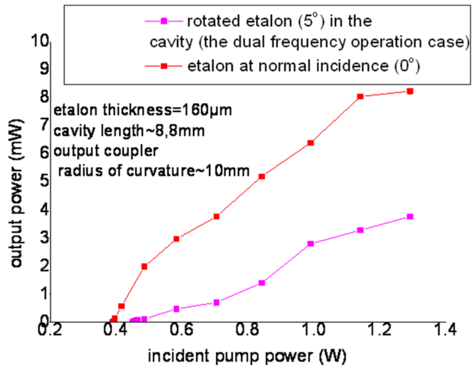

Figure 8: Influence of the rotation of the intra-cavity Fabry-Perot etalon on the output power.

On the other hand, also using the same output coupler, Figure 8 shows that a slight rotation of the F-P etalon causes high intra-cavity losses.

Finally, Figure 9 shows the effect of the output coupler reflectivity on the laser efficiency and maximum output power.

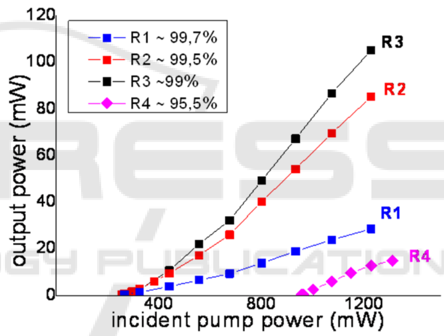

Figure 9: L-P curves obtained for different output coupler reflectivities.

The L-P curves depicted in Figure 9 were all obtained for a cavity mode waist close to 40µm.

It can be seen that up to 100-mW output power can be obtained by changing the reflectivity of the output coupler. This result indicate that more than 50 mW output power may be expected in dual-frequency laser operation by replacing our actual output coupler by another one having a reflectivity coefficient closer to R3~99%. This value is compatible with both spontaneous and stimulated Brillouin scattering.

2.4.2 Influence of the Fabry-Perot Etalon on the Stability of the Laser Emission

It is crucial to maintain single-longitudinal lasing on each of the two polarizations in order to obtain a stable, dual-frequency laser emission. Therefore the

FSR of the intra-cavity F-P etalon must be large enough to avoid simultaneous lasing of cavity modes located at different successive transmission maxima of the F-P etalon. For this reason, we have replaced the 160-µm thick SiO_2 etalon (FSR = 5 nm) by another one (SiO_2, thickness of 50µm and FSR =13nm). It is observed that it is easier to select a single cavity mode with a larger FSR of the etalon. However in this case a dual-frequency emission with frequencies largely separated (up to 30 GHz) is generally obtained, and the frequency difference is not stable as illustrated in Figure 10.

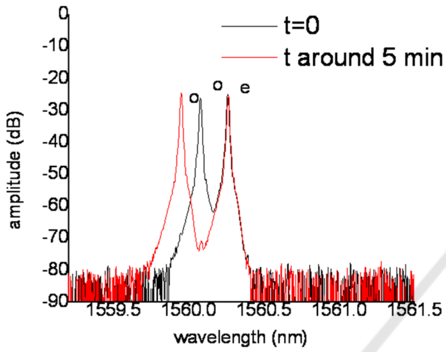

Figure 10: Evolution with time of the optical spectrum of the dual-frequency laser emission with a 50-µm thick SiO_2 F-P etalon having a FSR of 13nm.

It can be concluded that an ideal F-P etalon would have a FSR close to that of the 50-µm thick SiO_2 etalon (FSR ~ 13 nm), and a bandwidth close to that of the 160-µm tick SiO_2 etalon to ensure stable dual-frequency laser emission.

2.4.3 Influence of the Birefringent Crystal on the Stability (through the Mode Coupling Strength)

By changing the thickness of the birefringent crystal, the spatial mode separation is affected and the mode coupling strength is thus modified. Since quantum wells have a homogeneous gain, a coupling strength too close to 1 will induce mode competition and unstable dual-frequency operation (Pal, et al., 2010). On the other hand widely separated modes (i.e. with a mode coupling strength near zero) may show uncorrelated noise and therefore a broader and less stable frequency difference. We have therefore investigated the influence of the mode coupling strength on the dual-frequency emission by changing the thickness of the YVO_4 plate. For a fixed cavity mode size, changing the spatial separation modifies the mode coupling strength. The optical spectrum of the dual-frequency emission obtained with a cavity length of 8.8mm, a 160-µm thick F-P etalon, and a 1-mm thick YVO_4 plate is reported in Figure 11. The mode separation is two times larger than with the 500-µm tick YVO_4 plate. Figure 11 shows that stable dual-frequency emission can be obtained. A similar result is found (not shown) for a 250-µm thick YVO_4 plate.

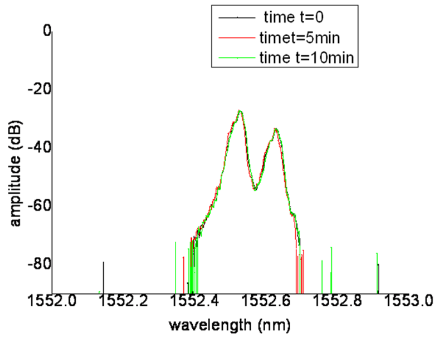

Figure 11: Optical spectrum of the dual frequency emission with a 1-mm thick YVO_4 plate (the coupling strength is lower than the case of a 500-µm thick YVO_4 plate). The spectral resolution is of 1 GHz.

2.4.4 Influence of the Mechanical Vibrations on the Stability without Active Stabilization

Finally we have examined the stability of the beat frequency in the MHz range. The experimental set-up is showed in Figure 12.

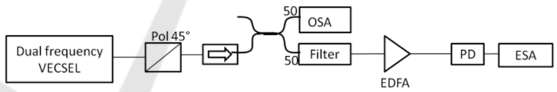

Figure 12: experimental set-up for measuring the beat frequency (Pol: Polarizer; OSA: Optical Spectrum Analyzer; EDFA: Erbium Doped Fiber Amplifier ; PD: photodiode ; ESA: Electrical Spectrum Analyser).

An optical polarizer with a 45° orientation is placed at the output of the dual-frequency VECSEL. The laser light is then injected in a 1x2 coupler, via an optical isolator. The first arm of the coupler is connected to the Optical Spectrum Analyser (OSA) while the second arm is connected to an Electrical Spectrum Analyser (ESA), for simultaneous measurement of both spectra.

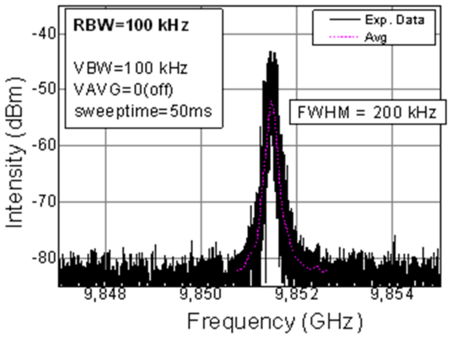

Figure 13: ESA spectrum for cavity length~8.8mm, output coupler radius of curvature=10mm, YVO4 500µm.

A typical signal corresponding to the frequency difference is shown in Figure 13. The full width at half-maximum (FWHM) can be estimated to be of the order of 200kHz. Dual-frequency VECSELs operating at 850nm and using a similar cavity configuration have shown a beat note FWHM of ~150 kHz without any active stabilzation (A.Camargo, et al., 2012), which is similar to the above result.

3 CONCLUSIONS

We have fabricated a VECSEL chip for laser emission at 1550nm, and we have assembled a VECSEL cavity for dual-frequancy operation at this wavelength. Stable dual-frequency emission with a frequency difference of ~11GHz has been obtained. Our experimental results show that more than 50mW output power can be expected in dual-frequency operation, which is compatible with the specifications of a Brillouin sensor. The optimization of the intra-cavity elements, namely the F-P etalon, can help to ensure a long-term stability of the dual-frequency emission without mode hoping. In the range explored in this work, the mode coupling strength has a low impact on the stability of the dual-frequency emission, allowing to adapt the cavity mode size to the pump spot size. Presently mechanical vibrations appear to be the main cause of the frequency difference instability. Similar dual-frequency VECSELs operating at other wavelengths have shown a similar RF signal linewidth without any active stabilization. As a conclusion, the design of a compact or mono-block cavity may allow to meet the stability specifications required for optical fiber Brillouin sensors.

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