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ABSTRACT

Since years, the VeCSEL concept is pointed out as a technology of choice for beyond-state-of-the-art laser light sources. The targeted coherent state in CW is typically the common gaussian TEM_{00}, single frequency, linearly polarized lightstate. In this work, we take advantage of the VeCSEL technology for the generation of other kinds of coherent states, thanks to the insertion of intracavity functions, such as low-loss intensity and phase filters integrated on a semiconductor chip. This technological development permitted to demonstrate very pure high-order Laguerre-Gauss mode, both degenerate and non-degenerate(vortex)modes, preserving the coherence properties of usual TEM_{00} VeCSELs. This technology paves the way for the generation of other coherences (Bessel beams) or new functionnalities (wavelength filtering, etc.). We also explore new time domain coherence : owing to a high gain semiconductor chip design and the insertion of intracavity AOM, we demonstrated the first Frequecy-Shifted-Feedback VeCSEL, with a broadband coherence state as wide as 300 GHz.

Keywords: VeCSEL,Photonic Crystal,Metallic Mask,High Order Mode,High Coherence, Continuum Laser,Vortex,Frequency Shifted Feedback .

1. INTRODUCTION

Since years, the VeCSEL concept is pointed out as a technology of choice for beyond-state-of-the-art laser light sources,[1,2] demonstrating wavelength flexibility,[3–8] high power,[8–11] high spatial, temporal and polarization coherence,[7,10] CW or fs ultra-short pulsed operation,[12–16] compactness and functionalities.[17–19] The targeted coherent state is typically a common circular low divergence fundamental gaussian TEM00 mode, linearly polarized state, single frequency state or modelocked comb. Such high-Q laser cavity exibits a class-A dynamics with low intensity noise at shot noise level in MHz-RF range, as well as a quantum limit optical frequency noise at the Hz level.[11,20,21] Integration and packaging of such high performances sources is in progress (by Coherent, Innoptics,[22] Fraunhofer ILT...).

In this work, we take advantage of diode-pumped VeCSEL III-V technologies (quantum-well, Bragg mirror, photonic crystal, metallic mask) and fundamental physical features (axial symmetry of the laser design, orthogonality of the cavity modes, high finesse/low losses operation, homogeneous gain, birefringence, dichroism, spatial hole burning...) for the generation of other kinds of highly coherent states, thanks to the insertion of new intracavity functions. These new kinds of large photon rate (high power) coherent states, close to the shot noise limit in the MHz-RF range, target many applications including optical tweezers, telecommunications, fundamental physics, sensors, spintronic...

A first part of this work aims at demonstrating new spatial coherent states, such as high-order Laguerre-Gauss modes, using the VeCSEL technology. Indeed, laser beams operating at high-order Laguerre-Gauss (LG) modes have lots of applications in many areas including laser drilling and writing, optical manipulation, trapping and

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guiding of atoms.[23, 24] Beyond the possible applications of the degenerate modes, the non degenerate modes, also known as optical vortices, are of particular interest since they carry orbital angular momentum as suggested by Allen et al.[25] In fact, the LG modes are the natural modes for a linear cavity using spherical mirrors and having axial symmetry of revolution.[26] We demonstrated that the Vertical External Cavity Surface Emitting Laser (VECSEL) is a very promoting laser technology for the generation of this kind of light beams.[7] Indeed, the VeCSEL design relies on small thickness quantumwell (QW) gain medium which minimizes non-linear optical interactions, thermal lens and possible astigmatism inside the semiconductor structure. The interplay of this 2 dimensions (2D) transverse gain medium with a low-loss cavity design permits the generation of single frequency high quality diffraction limited beam profiles, and we show that this is still true for high orders mode generation if we insert the suitable elements in the laser cavity.

In a second part, we explore a new time domain coherent state, to generate a continuum broad band light in CW:[27, 28] owing to a high gain broadband GaAs-based semiconductor structure design, a high finesse stable cavity design including an intracavity Acousto-Optic-Frequency-Shifter, we demonstrated the first GaAs-based modeless Frequency-Shifted-Feedback VeCSEL emitting around $1\mu m$, with a Fourier-Limited broadband continuum coherent state. It exhibits an optical spectrum as wide as 300 GHz and a coherence time $> 10ms$ in a TEM00 beam.

2. CONTROLLING THE TRANSVERSE MODE EMISSION

The generation of any LG mode (including LG_{01}/TEM_{00}) can be obtained by spatial filtering, taking advantage of modes competition to select a single transverse mode. The first way consists in reshaping/filtering the pump beam in order to obtain a better overlap between the gain and the wanted mode compared to the other modes.[29] Another way consists in performing some intracavity filtering, as demonstrated in[30] with a Nd:YAG laser using absorption filters. A similar architecture could be used in a VeCSEL and this may correspond to fig. 1-b.
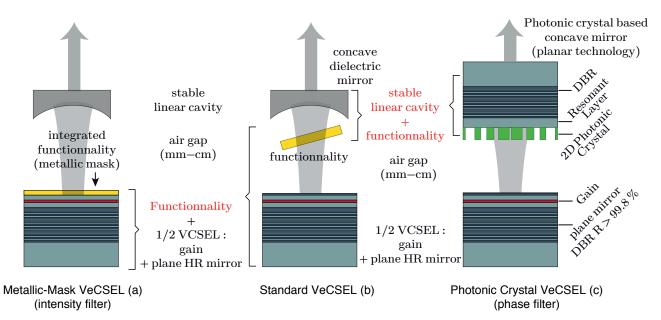

Figure 1. VeCSELs discussed in this paper. a) A metallic-Mask VeCSEL developed in the frame of this work. The aim is to integrate an absorbing spatial filter inside the cavity in order to promote a given mode of the LG base and give rise to its emission. b) A standard VeCSEL with the insertion of a given functionnality, like in any DPSSL. c) A photonic-crystal VeCSEL, developed in the frame of this work. The aim is to control the transverse phase of the beam inside the cavity, but advanced engineering leads to transverse intensity or laser spectrum control.

Introducing intracavity elements produce losses to unwanted modes of course, but unfortunately the wanted mode experiences additional losses too. If they remain strong ($\approx$ 1%), they lead to a drastic reduction of the output power but also to the photon lifetime, leading to low coherence emission. Moreover, using discrete intracavity elements lead to bulky designs. For those reasons, we developed technological steps permitting both integration and low-loss operation, enabling high coherence emission, high power and compacity.

2.1 The technology

In this work, we developed technological processes and careful designs, not only for transverse intensity but also transverse phase control inside the cavity, exploiting integrated III-V semiconductor planar technologies.

For a robust low-loss control of the intensity only, we deposited very thin metallic masks ($\approx 5nm$) on the surface of the chip (fig. 2-a), leading to a laser design corresponding to set-up fig 1-a. Thanks to the VeCSEL configuration, these masks provide both pump reshaping and intracavity absorption filtering. Concerning the absorption of the unwanted modes, the metallic masks were intentionally placed at a maximum of the electrical field for the targeted emission wavelength in order to improve the filter efficiency. Such a control of the filter position in the field is natural using the VeCSELs technology, and is not possible with traditionnal DPSSL or laser diodes for example. This is however an important feature as it permits the targeted low loss operation.
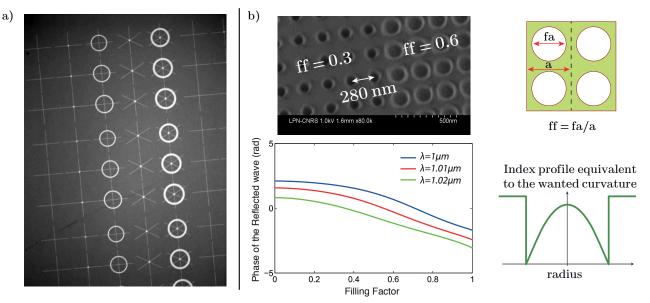

Figure 2. a) Picture of the metallic masks deposited at the surface of the 1/2 VCSEL, permitting the generation of various modes chosen in the LG base. The typical size of each pattern is $\approx 250\mu m$. b) Scanning electron microscope picture of the PC structure (period 280 nm) for the maximum step index. Large holes = 0.6 filling factor; small ones = 0.3. PC Phase variation curves as a function of the filling factor, and targeted phase profile for a concave mirror.

For phase control, we developed a low-loss hybrid 2D photonic-crystal deposited on a Bragg mirror using the planar III-V semiconductor techniques. The first step was to demonstrate a low-loss, high reflectivity and aberrations free Photonic Crystal bragg Mirror with focusing capability, for single mode cavity operation, able to stabilize a TEM00 with low losses in a laser cavity configuration. This mirror was engineered and permitted to reach the laser operation in a configuration corresponding to fig. 1-c.

To obtain the adequate design we used Rigorous Coupled Wave Analysis (RCWA) and reached the dispersion curves as function of the fill factor ff (Fig. 2-b), which is defined by :

$$ff = \frac{\text{hole diameter}}{\text{PC period}} = \frac{fa}{a} \tag{1}$$

The semiconductor structure holding the PC was grown by MOCVD on GaAs substrate : the multilayer DBR is made of AlAs/GaAs layers, the last layer being a GaAs spacer; on top, a 312nm thick SiN was deposited by sputtering; finally after an e-beam lithography of the SiN layer (1.25nm resolution), the holes of the PC were obtained by reactive ion etching (Fig. 2-b).

2.2 Laser operation results

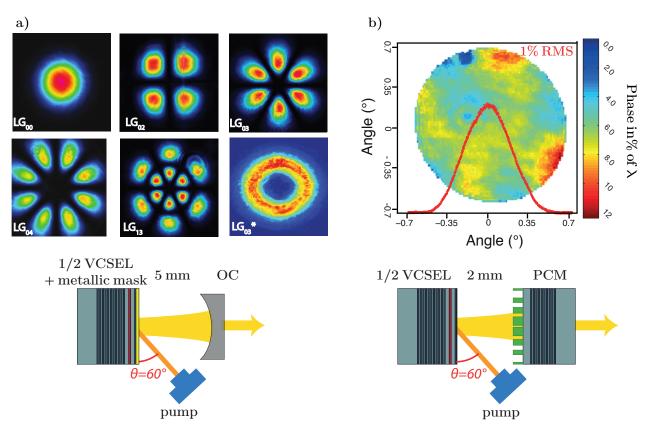The results obtained with both technologies are summed-up in fig. 3.

Figure 3. a) High order degenerated and non-degenerated Laguerre-Gauss modes obtained experimentally with metallic masks and a 5mm VeCSEL cavity. b) Optically stable aberration-free VeCSEL cavity based on planar technology thanks to the transverse control of the phase inside the laser cavity thanks to the photonic-crystal mirror technology.

As expected, this technological development permitted to control the intensity and / or the phase of the laser beam inside the cavity, allowing the selection of any degenerated or non-degenerated chosen high order LG mode (fig. 3-a) or to a high purity TEM00 emission (phase fluctuation RMS < 1% fig. 3-b) with a free space cavity based on pure planar technology, enabling low-loss aberration-free operation. Both technologies exhibit ultimately low-losses, with thresholds always $< 2.1 kW/cm^2$ and output power $>> 10mW$. Moreover, all these lasers demonstrate single frequency operation with SMSR as high as 45 dB or even stronger. Simulations demonstrate a rejection of the unwanted transverse modes by more than $80dB$.

The non-degenerated LG mode (Vortex) emission depicted in fig. 2-b was specifically studied thanks to an interferometric set-up, which allowed to observe the characteristic fork for helical phase structure with topological charges +-1 and +-2.

3. COHERENT CONTINUUM GENERATION

Coherent light in CW usually means single frequency operation with the narrowest linewidth. This is mainly due to the fact that most broadband sources emit principally spontaneous emission, leading to a random phase

spectrum. At the opposite, a modeless laser is a device which provides intense coherent broadband light fields. It finds applications in areas such as high resolution spectroscopy, medicine, radar-lidar, metrology[27]where a coherent broadband radiation is needed.

In a modeless laser, the constructive interference of the optical wave, which would lead to spectral mode structure, is prevented by the insertion of an intra-cavity frequency shift on each round trip. In order to eliminate the mode structure, the frequency shift should occur by a mechanism which does not simultaneously change the cavity length. A common technique to achieve this is to use an acousto optic frequency shifter device (AOM) that will cause a discrete frequency shift of $\Delta = 2 \times \nu_{AOM}$ on each round trip. We note that in order to achieve broadband continuous emission the ratio of $\Delta/FSR > 0.01$[28] where FSR is the free spectral range of the cavity without AOM. This way, we can reach a wideband coherent spectrum, because the phase shift is not due to the random events of spontaneous emission but to the deterministic acoustic wave inside the AOM. The phase spectrum of the modeless laser is thus well determined and no more random.
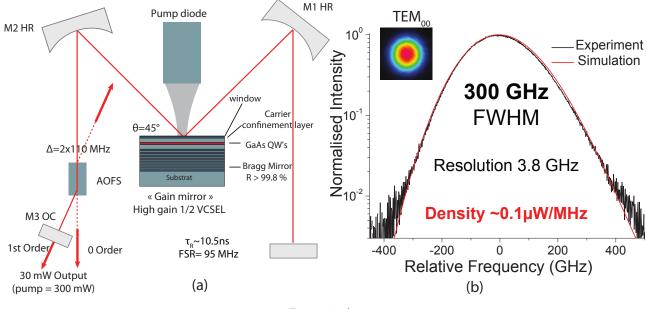

Figure 4. a)

In this work, we demonstrate for the first time a 300GHz bandwidth (FWHM) continuous wave operation of a modeless Vertical External Cavity Surface Emitting Laser. The laser cavity design (fig. 4-a) is based on a frequency-shifted-feedback laser design using an intracavity acousto optic frequency shifter with $\nu_{AOM} = 110MHz$ and 92% 1st order diffraction efficiency. The gain is provided by high gain GaAs based multiple quantum well (12QW) semiconductor chip emitting at 1070nm. This semiconductor structure includes a backside DBR HR mirror (99.9%). It is pumped with a 250mW single-mode pump (785nm), focused on the semiconductor chip with a $50\mu m$ waist. To reach a low laser threshold operation, a M-shaped cavity has been designed (overall length of 1.5 m) as it permits two passes per round trip in the gain medium, compared to linear cavities. The emitted power reached 30mW, with TEM$_{00}$ emission and strongly linear polarization ($> 20dB$).

4. CONCLUSION

We demonstrated that Vertical External Cavity Surface Emitting Laser (VECSEL) is a very promoting laser technology to achieve high power semiconductor laser emitting new kinds of spatial or spectral coherence.

These GaAs-based devices allow the generation of highly coherent - degenerated or non generated - high order Laguerre-Gauss mode(s), preserving the spatial, temporal and polarization coherence properties (diffraction

limited beam, ultra low noise, highly linear polarization) of usual TEM00 VeCSELs. We also demonstrated low divergence highly coherent VORTEX beam,[25] standing-wave radial pattern beam, dual-frequency operation for THz generation, with a linewidth quantum limit at the Hz level and a $RIN < 140dB_{/Hz}$. It also paves the way for the generation of other coherent states (Bessel beams, circularly polarized beams...) exploiting new functionalities (spectral filtering, birefringence, dichroism, chirality...).

The generation of wideband coherent light is also demonstrated thanks to a high gain 1/2 VeCSEL structure. Modeless VeCSELs are specifically interesting compared to other modeless lasers as they take benefit in III-V semiconductor systems, giving flexible wavelength choice and allow specific-application-intended design of the gain medium compared to other material gain systems. They also permit to envisage compact designs and short cavities, enabling long range detection. Time domain coherence can also be increased further by technological development and gain medium engineering. Injection-seed modeless laser can be used in pulsed operation with low jitter and repetition rates from few GHz to 20 GHz to tackle specific application like optical sampling of electrical signals.

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