

Spatial and spectral mode filtration in phase-locked array of injection lasers with volume Bragg grating

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Abstract. High-power edge-emitting lasers with low divergence of the output beam are highly desired for a number of applications. In order to obtain high optical power one needs to expand the emitting area of the laser which usually leads to multi-mode lasing with broad spectrum and poor beam quality. Here we present the study of using a volume Bragg grating (VBG) as a spatial and spectral mode filter for phase-locked arrays of edge-emitting lasers based on 1D photonic bandgap crystals. Emitters in the arrays are synchronized due to the expanded vertical waveguide, which results in the lasing of high order oscillating modes. One lobe of high order mode was used to create an external cavity with VBG. We studied far-fields, spectra and L-I curves of the external cavity lasers and demonstrated that *500 mW* of the output optical power could be concentrated in one lobe with the divergence as low as 1° and spectral width of *0.6 nm*.

Introduction

High power semiconductor laser with high spatial and spectral brightness are desired for a number of applications such as pump systems for solid state and fiber lasers, material processing, medicine, etc. [1-3]. To achieve high power from edge-emitting lasers and reduce output beam divergence one needs to expand waveguide both in lateral and vertical directions. This usually results in poor spatial and spectral quality of laser beams. Several approaches have been proposed to keep single mode lasing in broadened waveguides [4,5]. However, many of them are rather sensitive to minor changes of refractive indexes of the waveguide layers [6]. On the other hand, such techniques as photonic band gap crystal (PBC) and tilted wave lasers (TWL) demonstrated ultra-narrow beam and robustness with respect to growth deviations and temperatures [7].

Broadened vertical waveguide allows obtaining low vertical divergence. However, for high power lasers it is critical to have broad emitting area and good beam quality in the lateral direction as well. Phase-locked arrays of edge-emitting lasers, which may produce narrower beam in lateral direction, have been investigated since early 1980s [8]. It has been shown that arrays of phase-locked



semiconductor lasers tend to lase in oscillating (out-of-phase) modes rather than in fundamental (in-phase) modes. Recently PBC lasers were used to create phase-locked arrays emitting in single vertical mode with the optical power as high as 15 W [9]. In these arrays modes of the adjacent emitters effectively overlap due to the broadened PBC waveguide. It has been shown that in PBC-based arrays, besides the loss selective mechanism [8], lateral modes are discriminated by their optical confinement factor [10]. Optical confinement factor is almost two times larger for the oscillating mode than for the fundamental one.

Oscillating modes of phase-locked arrays have two narrow lobes in the far field pattern. The lateral divergence of the output beam from the phase-locked arrays can be as low as 5° (FWHM). Two lobes from oscillating modes can be collimated in one with additional optical elements [11]. On the other hand, progress in recording volume Bragg gratings (VBG) in a glass makes it possible to create external cavities with minimum additional optical elements [12]. With modern VBG it is possible to achieve angular selectivity about 0.05° and spectral selectivity about 0.1 nm in wavelength range of $1\ \mu\text{m}$, which should be enough to pick out single lateral modes from phase-locked arrays. Hence, one lobe of the oscillating mode can be used for the external feedback with VBG and another as an output beam, resulting in only one narrow lobe in far field of the external cavity laser.

In this paper we present the study of using a VBG as a spatial and spectral mode filter for arrays of phase-locked edge-emitting PBC-based lasers.

Laser design

The laser wafer was grown by MOCVD on GaAs substrate. Nine pairs of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ were deposited to form PBC structure. Three QW $\text{In}_{0.19}\text{Ga}_{0.81}\text{As}/\text{GaAs}_{0.86}\text{P}_{0.14}$ in the top $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ layer of PBC serve as an active medium and simultaneously as an “optical defect” to localize the mode. Bottom layers of PBC were doped with Si and serve as n-emitter. Thick p-doped layer of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ was grown on the top of PBC to form p-emitter. The total thickness of the PBC waveguide is $\sim 10\ \mu\text{m}$. More details on the structure design can be found elsewhere [9].

The phase-locked arrays consisted of 23 emitters with the width of $4\ \mu\text{m}$ formed by standard photolithography (figure 1). Distance between emitters was $5\ \mu\text{m}$. Therefore, the total width of the lateral waveguide was as high as 0.2 mm . The cavity length was 1 mm . Facets were coated by high-reflection (95%) and anti-reflection (3%) coatings. The lasers were mounted p-side down on copper heat-sinks. The lasing wavelength lies in the range of 970-980 nm at 20°C .

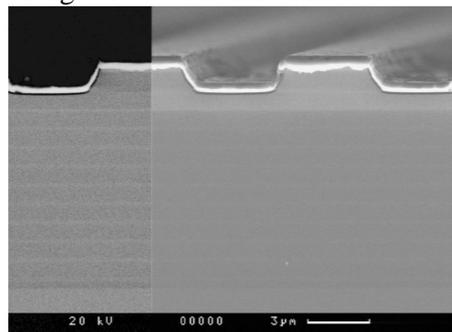


Figure 1. SEM image of the cross-section of PBC-based laser array.

Volume Bragg Grating was recorded in photo-thermo-refractive glass. The size of the grating is $10\times 10\times 1.5\text{ mm}$. It has maximum reflectivity of 94% at 982.1 nm at room temperature. Spectral width of reflection on half maximum is 0.6 nm , angular selectivity is less than 1° .

Figure 2 shows the scheme which we used to create the external cavity. First cylindrical lens with 3 mm diameter collimated the beam in the vertical direction. Second plano-convex cylindrical lens was used to focus laser beam on the VBG. Lenses were uncoated and made of NBK-7 glass which is suitable for near IR range. Focal length of the second lens is $\sim 24\text{ mm}$ at 980 nm. This scheme is very

convenient for experiments and allows scanning lateral far fields of external cavity lasers. To adjust the cavity we rotated VBG. When VBG planes become normal to a certain mode lobe, emission of this lobe comes back into the array creating external feedback. Laser temperature was stabilized at $\sim 50C$ in order to match the lasing wavelength to the VBG reflection. As the laser temperature was quite high, all measurements have been done in pulsed regime in order to avoid additional overheating.

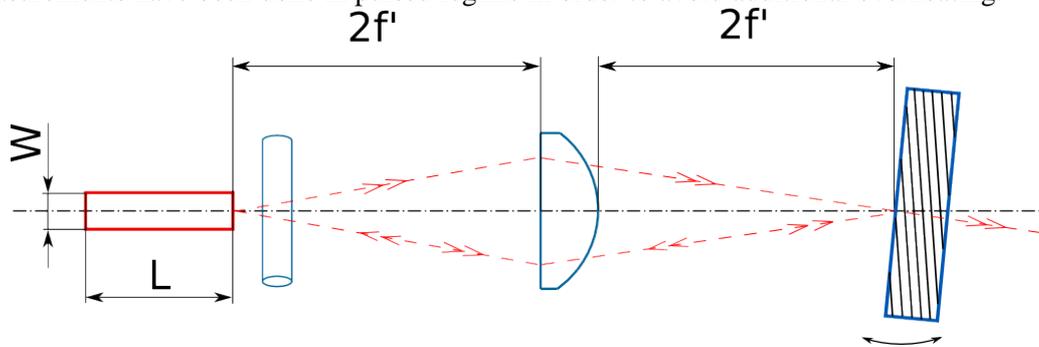


Figure 2. Scheme of external cavity with VBG. $W=0.2mm$, $L=1\text{ mm}$, $f' = 24\text{ mm}$. Layers of heterostructure are parallel to draw plane. Lateral far fields were measured by the rotating rod with a detector coaxial with VBG.

External cavity laser characteristics

We obtained similar results for all studied array samples. External cavity optical scheme has two symmetric VBG orientations. We have used an orientation with the best far field (2.55° , figure 3). Figure 3 shows lateral far fields (a) of free running array and external cavity laser. Pump current was slightly above the threshold. It is clearly seen that the free running array has two sharp lobes in the far field which indicates that it lases in oscillating modes. External cavity laser has one sharp (1°) lobe and two small satellites in the far field. Linewidth of 0.6 nm (figure 3b) of the external cavity laser corresponds to the of VBG reflection linewidth.

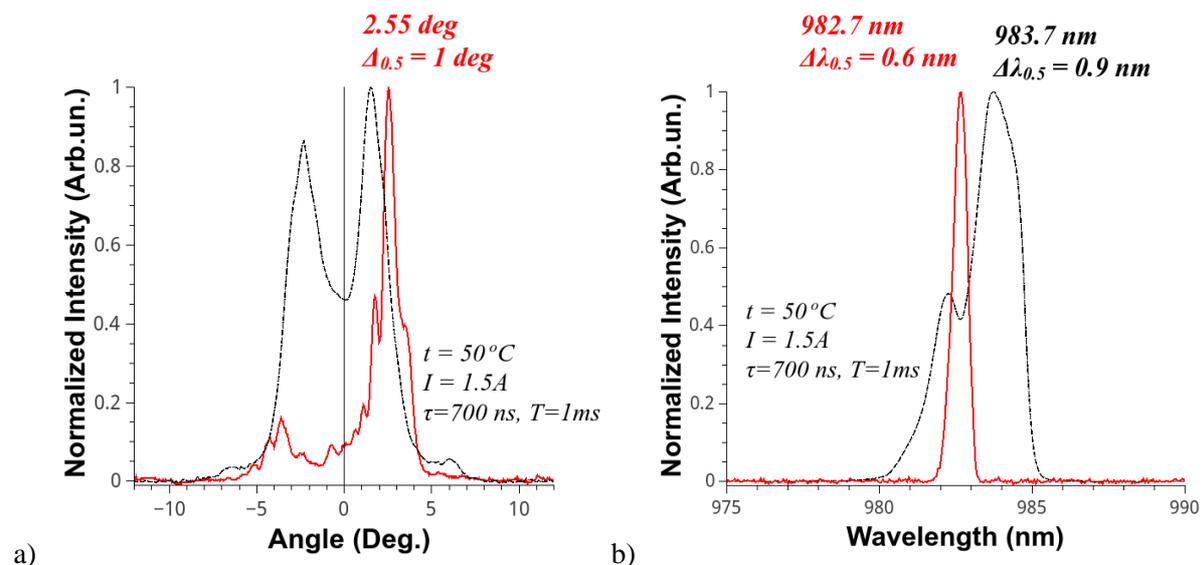


Figure 3. Lateral far field (a) and spectrum (b) of free running (dashed) and external cavity (solid) laser.

We measured L-I curve from free running array and external cavity laser (figure 4). Differential efficiency dropped by 30%, threshold current almost unchanged. Differential efficiency can be improved by using anti-reflective coated lenses. Lateral far field and spectrum remained the same with

rising pump current up to 8A. At the current of 6A, 500mW of the optical power was concentrated in one lobe with the divergence of 1° and linewidth of 0.6 nm.

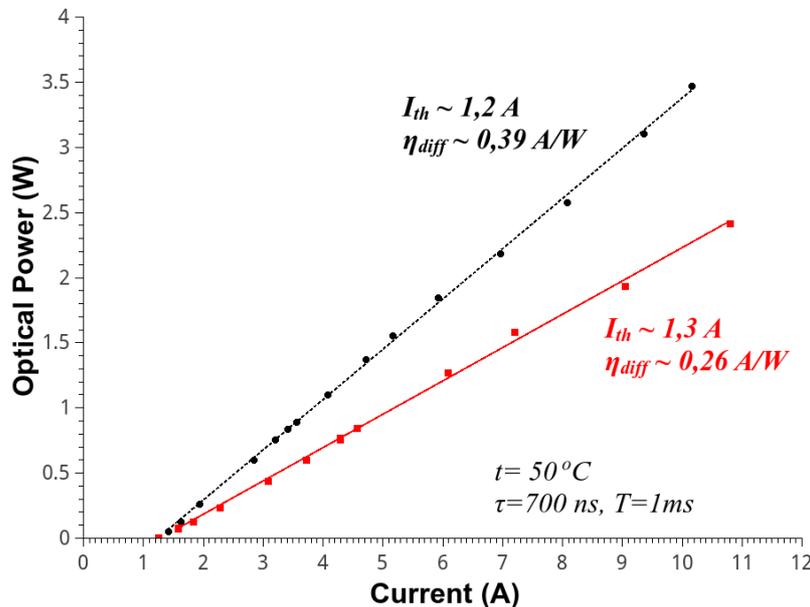


Figure 4. L-I characteristics of free running (dashed) and external cavity (solid) laser.

Discussion

The threshold current of the free running laser is almost the same as one of the external cavity laser (figure 4). We believe that the external cavity laser operates in a combined regime: it has feedbacks both from the laser chip facets and from the VBG. In this case of coupled cavities, the lasing wavelength is not entirely defined by the VBG spectral parameters, which may result in wavelength pulling from the VBG reflection maximum [13]. This effect is clearly seen in figure 3b. By suppressing a feedback from the laser chip facet a “standard” VBG laser operation reported elsewhere [12] can be obtained.

Satellite lobes in the far-field seem to indicate multi-mode operation of the external cavity laser. To avoid multi-mode lasing one can try to use a thicker VBG with better angular selectivity.

We believe that with optimized relation of feedback between two cavities one can improve characteristic of external cavity phase-locked laser array.

Conclusion

We have demonstrated for the first time that volume Bragg grating allows filtering oscillating modes in phase-locked arrays of PBC-based semiconductor lasers. VBG-based external cavity lasers have one narrow lobe in the far field with significant amount of optical power concentrated in this lobe. Spectral linewidth of external cavity lasers is defined by VBG and does not depend on the pump current. One can expect that the use of coated lenses in external cavity and optimization of anti-reflection coating on the laser facets may further improve characteristics of the external cavity lasers.

Acknowledgements

The authors are grateful to Prof. Leon Glebov, Photoinduced Processing laboratory, CREOL / The College of Optics & Photonics, University of Central Florida, for providing the volume Bragg gratings.

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