Growth and testing of vertical external cavity surface emitting lasers (VECSELs) for intracavity cooling of Yb:YLF

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Abstract:

Optically-pumped Vertical External Cavity Surface Emitting Lasers (VECSELs) have unique characteristics that make them attractive for use in intracavity optical cooling of rare earth doped crystals. We present the development of high power VECSELs at 1020 nm for cooling ytterbium-doped yttrium lithium fluoride (Yb:YLF). The VECSEL structures use AlAs/GaAs distributed Bragg reflectors and InGaAs/GaAsP resonant periodic gain epitaxially grown by metal-organic vapor phase epitaxy. To achieve the necessary output power, we investigated thinning the substrate to improve the thermal characteristics. We demonstrated a VECSEL structure that was grown inverted, bonded to the heat sink, and the substrate removed by chemical etching. The inverted structure allows us to demonstrate 15 W output with 27% slope efficiency. Wavelength tuning of 30 nm around 1020 nm was achieved by inserting a birefringent quartz window into the cavity. The window also narrows the VECSEL emission, going from a FWHM of 5 nm to below 0.5 nm at a pump power of 40 W.

Introduction

Laser-based optical cooling of rare-earth doped insulator crystals has the potential for achieving a solid-state cryogenic system. Such a cryogenic system would have no moving parts to wear out, would lack cryogenic fluids that could leak, would be vibrationless leading to low image blur, and could be much smaller than current systems. Early demonstrations of solid-state optical cooling used externally pumped cavities to achieve cooling of ytterbium-doped yttrium lithium fluoride (Yb:YLF) [1,2]. The amount of absorbed power determines the cooling capacity and efficiency achieved. Placing the Yb:YLF crystal in a laser cavity would increase the absorbed power. Vertical external cavity surface emitting lasers (VECSELs) easily accommodate intracavity elements. VECSELs have demonstrated high output powers [3] and high efficiencies [4] making them well suited for pumping a Yb:YLF crystal. Semiconductor quantum wells have high optical gain and can be coarsely tuned through adjustment of quantum well thickness. These facts lead us to develop VECSELs at 1020 nm and characterize their output power.

A VECSEL requires several subsections to work together simultaneously. We used temperature dependent reflectivity to evaluate if the QW resonance is accurately placed spectrally with respect to the Fabry-Perot (FP) and the resonant periodic gain (RPG) region. This evaluation allowed us to account for the elevated temperature the VECSEL operates at. We demonstrated the importance of minimizing thermal resistance for achieving high output power. We reduced the substrate thickness to improve the maximum output power. To achieve the minimum thermal resistance, we designed an inverted VECSEL structure that eliminates the thermal impedance associated with the GaAs substrate.

Experimental

All investigated VECSELs were grown by low-pressure metal-organic vapor phase epitaxy (MOVPE). The MOVPE system uses a high-speed rotating disk chamber at 500 rpm and operates at 60 Torr. The chamber is equipped with optical monitoring for measuring *in situ* wafer reflectance and surface temperature using emissivity corrected pyrometry. Structures were grown on semi-insulating GaAs (100) wafers with a 2° miscut toward (110). The substrate wafer was heated to 730°C for 15 min under a flow of AsH_3 and H_2. The wafer was subsequently cooled to 650°C for the all the remaining growth. AsH_3 and PH_3 provided group V elements. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and trimethylindium (TMIn) metal-organics supplied the group III elements. No dopants were used as the structure is optically pumped.

The VECSEL can be divided into two sections. The distributed Bragg reflector (DBR) consisted of 24 quarter-wavelength pairs of AlAs and GaAs. We used the binary compounds to minimize the thermal resistance associated with AlGaAs alloys.[5,6] The AsH_3 flow was held constant at 100 sccm during DBR growth. For AlAs growth, 37 μmol/min of TMAl achieved 21 nm/min growth rate. For GaAs, 37 μmol/min produced a growth rate of 21 nm/min. The V/III ratio for the DBR was kept at 120. For the RPG region, the AsH_3 flow was reduced to 60 sccm. Homogeneous half-wavelength thickness $GaAs_{0.97}P_{0.03}$ layers separated $In_{0.23}Ga_{0.68}As$ QWs. $GaAs_{0.97}P_{0.03}$ was grown by adding 15 sccm PH_3 to the established flows of AsH_3 and TMGa, giving a V/III ratio of 90. The $In_{0.23}Ga_{0.67}As$ QWs were formed by adding 11 μmol/min TMIn to the established TMGa and AsH_3 flows for a V/III ratio of 56. $GaAs_{0.97}P_{0.03}$ was used to provide strain compensation and improve performance, but active regions grown with GaAs separation layers had similar PL intensity and linewidth. We assess if strain strain compensation is necessary to achieve high VECSEL performance at the targeted wavelength. All VECSEL structures utilized twelve QWs in the RPG region. The VECSEL structure was capped with half-wavelength $In_{0.49}Ga_{0.51}P$ to provide surface passivation. The $In_{0.49}Ga_{0.51}P$ was grown using 26 μmol/min TMIn added to the TMGa flow, using a V/III ratio of 140. The inverted design used the same elements and conditions described above. The exception is that a 300 nm AlAs etch stop layer was grown first followed by the $In_{0.49}Ga_{0.51}P$ passivation layer, the RPG region, and the DBR.

The standard structures were grown on single-side polished GaAs wafers, allowing easy measurement of the Fabry-Perot (FP) resonance generated by the thickness of the RPG region. This assessment was done with temperature dependent reflectivity (TDR) in a Fourier Transform infrared spectrometer. The wafer was contacted with a thermoelectric stage, allowing the temperature to be raised about 100°C above ambient. Figure 1a illustrates the spectra obtained from such a series of measurements. As the temperature increased, the FP resonance overlapped with the resonance associated with the InGaAs QWs, producing a pronounced dip in the reflectivity. The overlap decreases at the highest temperatures when the two resonances no longer overlap. This effect was modeled using the known temperature dependence of the GaAs index of refraction as an approximation for $GaAs_{0.97}P_{0.03}$ [7] and assuming the temperature shift of the $In_{0.23}Ga_{0.77}As$ QW is equal to that of bulk GaAs [8]. Figure 1b displays the modeled shift in wavelength of the RPG FP resonance and the QW resonance. The FP shift is 0.05

nm/K, while the QW shift is 0.4 nm/K. The model predicts the minimum reflectance to be at 365 K, which compares favorably to the experimental minimum of 360 K. The minimum in reflectance identifies the optimal VECSEL operating temperature

The as-grown standard VECSEL was mounted on copper using thermal grease for testing. When the standard VECSEL was thinned to approximately 100 μm, the backside was metalized with 50 nm Ti and 100 nm Au followed by 2 μm of In. This was contacted with thermal grade polycrystalline CVD diamond with the same metallization to form a mirror sandwich and the stack was heated under compression at 200°C for an hour. A similar bonding method was used for the inverted VECSELs. For the inverted VECSEL, removal of the GaAs substrate was accomplished with a flowing stream of 7:1 $NH_4OH:H_2O_2$. The AlAs etch stop was removed in $HF:H_2O$ solution, which stops on the InGaP surface passivation layer.

To test the VECSEL performance, a simple external cavity was constructed as illustrated in Figure 2. A 1% transmission, 25 cm radius of curvature output coupler (OC) serves as the external mirror. The OC was placed 24.5 cm from the gain chip. The resulting mode size at the VECSEL sample is matched to the roughly 300 µm diameter pump spot created by focusing a fiber-coupled 808 nm pump diode laser. In some experiments a birefringent window was placed in the cavity, introducing variable loss and a mechanism to tune the laser wavelength.

Results and Discussion

The as-grown standard VECSEL perform poorly. Figure 3 shows the L_{in}-L_{out} curve for this laser. The maximum output power is only 230 mW at a 5.4 W input power with slope efficiency of only 6 percent. The threshold power is reasonable at 1.5 W (2 kW/cm^2). Thinning the standard structure improved the performance as shown in Figure 3. The threshold power is similar to the as-grown case. This result is expected, if thinning introduces minimal damage. Thinning increased the maximum output power by a factor of six and improved the slope efficiency. Substrate thinning by lapping yielded results with significant variability. The results reported in Table I are the best performance obtained. Several of the thinned wafer chips had maximum output powers lower than 1.5 W. The improvements obtained by thinning the substrate suggested the direction for improved VECSEL performance.

The inverted VECSEL represents a significant improvement in performance compared to previous results. Figure 4a shows the L_{in}-L_{out} curves for the inverted VECSEL using both 1 and 5 percent output couplers. The output power is limited by the maximum pump power produced by our equipment. The peak output powers were 10 and 17 W for the 1 and 5 percent output couplers, respectively, and the slope efficiencies obtained were 18.5 and 27.2 percent for the two cases. While the thermal characteristics of the inverted VECSEL are vastly superior, a detailed comparison to the thinned structure suggests both designs produce similar output powers at comparable input powers, below thermal rollover. This suggests the operation of the two designs are very similar and no degradation is introduced by growing the VECSEL inverted. Figure 4b shows the red-shift of the VECSEL as the incident power increases, consistent with the expected heating of the RPG region. Figure 4b also illustrates the growth of the linewidth of the VECSEL beam as the output power increases. This expansion of the linewidth is typical for VECSELs and is attributed to the excitation of higher order modes in the cavity as the pump power increases. We investigated techniques to stabilize a single wavelength and achieve a narrower linewidth.

A birefringent quartz filter inserted into the cavity as indicated in Figure 2 produces an etalon for a specific wavelength supported by the QW gain.[9] By varying the angle of the filter with respect to the beam, narrow linewidth emission (0.5 nm) can be obtained at several different wavelengths as shown in Figure 5. This experiment effectively traces the gain curve suggesting the current design has gain between 1000 and 1030 nm. The linewidth reduction is remarkable given that the spectrum taken at 32.8 W shown in Figure 4b has a FWHM of 5 nm. This is important for laser cooling of Yb:YLF as the E4 – E5 transition shifts slightly as the sample cools and slight tuning will improve coupling. The effect is also relevant because the absorbance of Yb:YLF decreases at lower temperatures, requiring higher cavity power to achieve the same adsorbed power. To achieve higher cavity power, higher pump powers are required, resulting in spectral red-shifts that need to be accommodated for.

Conclusions

VECSELs based on GaAs/AlAs DBRs and GaAsP/InGaAs RPG region have been demonstrated with sufficient output powers for laser cooling applications. We optimized the spectral overlap of the QW absorbance with the cavity absorbance using temperature dependent reflectivity. A model predicts the observed spectral overlap by accounting for the temperature dependence of the relevant resonances. The VECSEL performance improved dramatically by minimizing the substrate thermal impedance and bonding the VECSEL chip to diamond heat spreaders with indium metal. The maximum output power and slope efficiency improved, but the threshold does not shift with different substrate thicknesses. Our results emphasize the importance of thermal management to achieve high VECSEL performance. We showed that the VECSEL spectrum can be narrowed and tuned by inserting a birefrigent quartz filter into the cavity. This filter allows the wavelength to be shifted to the E4-E5 transition of Yb:YLF at 1020 nm. We have been able to apply these VECSELs to intracavity optical cooling of Yb:YLF down to 148 K.[10]

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Captions

Table I. Comparison of VECSEL performance for VECSELs discussed. The * indicates that while this is the maximum performance obtained we did not observe thermal rollover, suggesting the performance could be higher.

Figure 1. (a) Temperature dependent reflectivity shows the shifting absorbance dip as the FP and the MQW resonances are tuned generating a minimum reflectivity at 360 K. (b) The modeled shift of the FP resonance (▲) and the QW resonance (■) with measurement temperature. The curves are regressions to the simulation showing the FP resonance shifts at 0.05 nm/K and the QW resonance shifts at 0.4 nm/K. The calculated crossing occurs at 365 K and compares favorably to the experimentally crossing of 360 K.

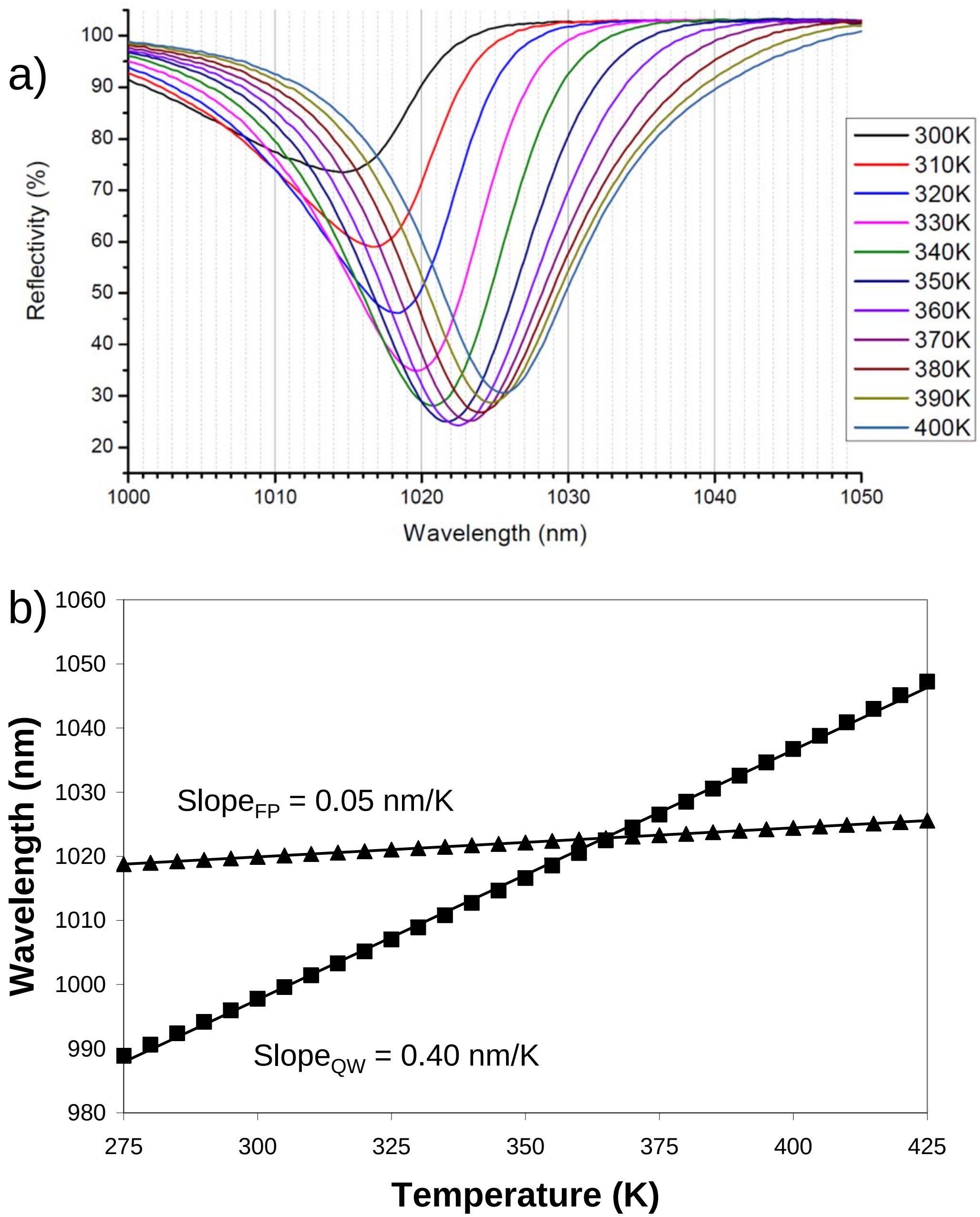
Figure 2. Diagram of the optical cavity used for VECSEL testing and evaluation. A birefrigent quartz window was introduced into the cavity to characterize the tuning range.

Figure 3. L_{in}-L_{out} curve for the as-grown (▲) and thinned (□) standard VECSELs. While the thinned standard structure has improved thermal characteristics compared to the as-grown structure, the output powers in both cases are too low for optical cooling applications.

Figure 4. (a) L_{in}-L_{out} curve for the inverted VECSEL metal bonded to a diamond heat spreader, showing cases for both 1% and 5% output couplers. (b) Spectra of VECSEL beam taken at 2.9 W incident power, slightly above threshold, and higher incident powers. At higher pump powers, the spectra display a red-shift and a broadening attributed to heating of the RPG region and excitation of more modes at higher pump powers.

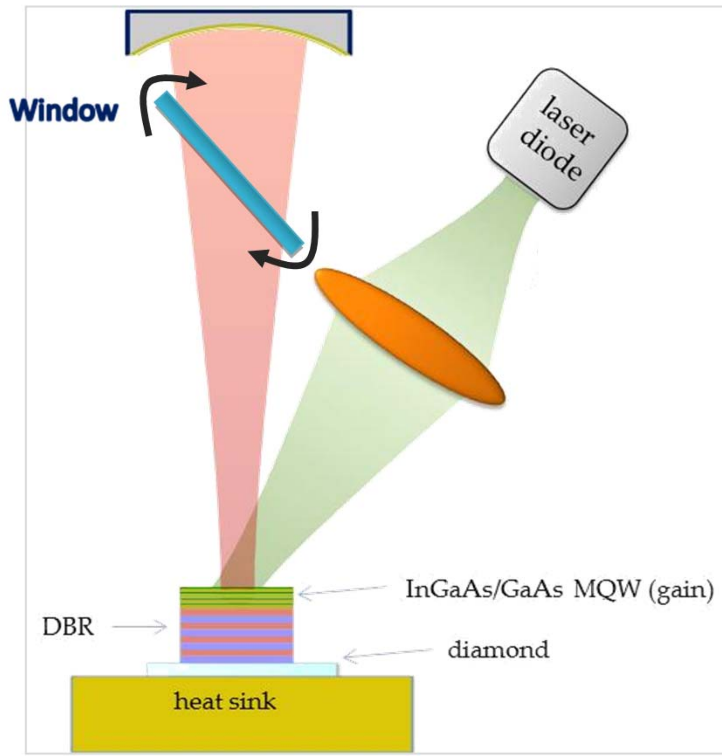
Figure 5. Dramatic reduction in spectral linewidth is achieved by introducing an intra-cavity birefrigent quartz filter into the VECSEL cavity. This allows tuning the wavelength over the available gain spectrum. The inverted VECSEL can be tuned by 30 nm at a pump power of 40 W.

Figure 1



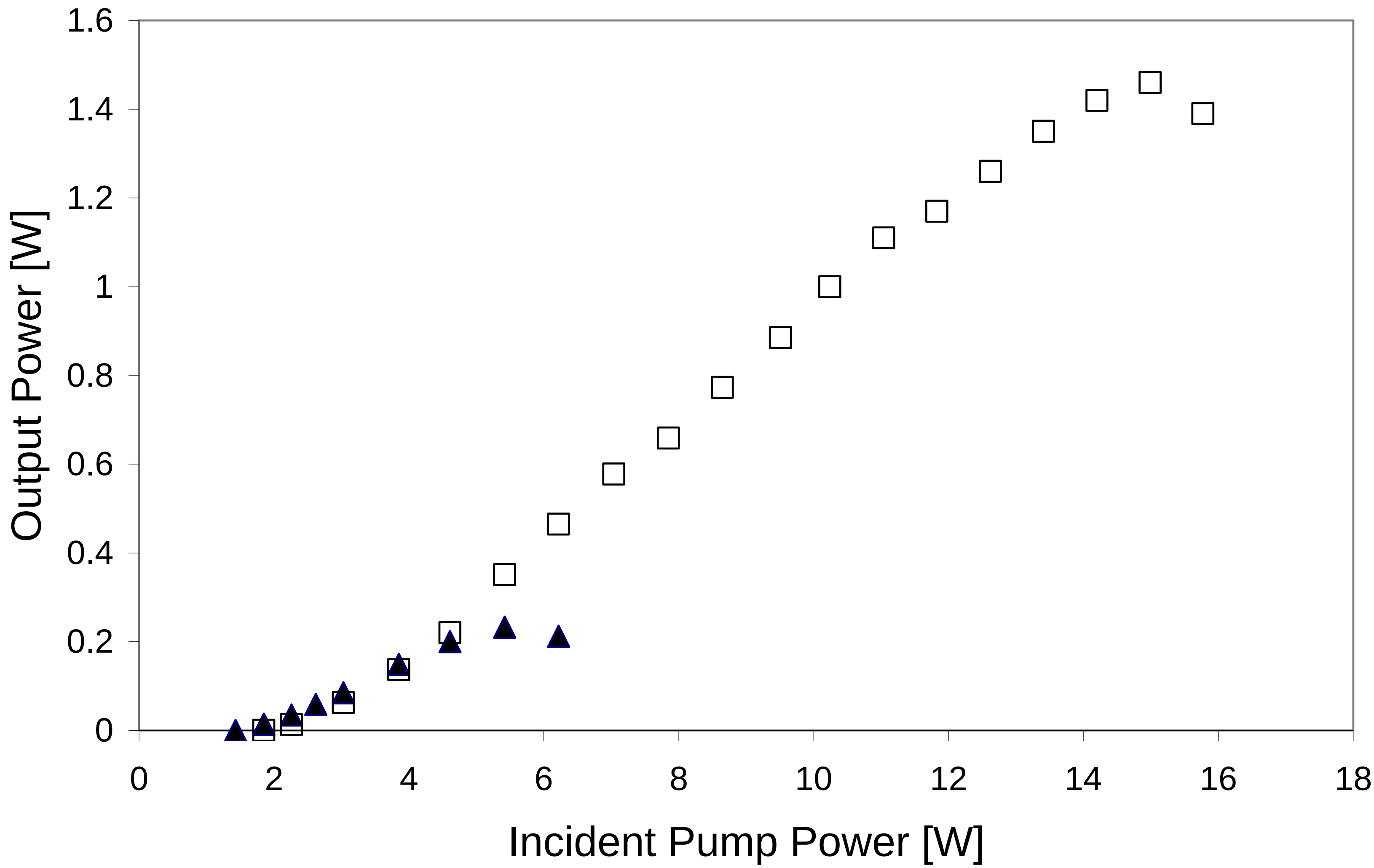
a)
Reflectivity (%)
100
90
80
70
60
50
40
30
20
1000
1010
1020
1030
1040
1050
Wavelength (nm)
300K
310K
320K
330K
340K
350K
360K
370K
380K
390K
400K
b)
Wavelength (nm)
1060
1050
1040
1030
1020
1010
1000
990
980
275
300
325
350
375
400
425
Temperature (K)
Slope$_{FP}$ = 0.05 nm/K
Slope$_{QW}$ = 0.40 nm/K

Figure 2



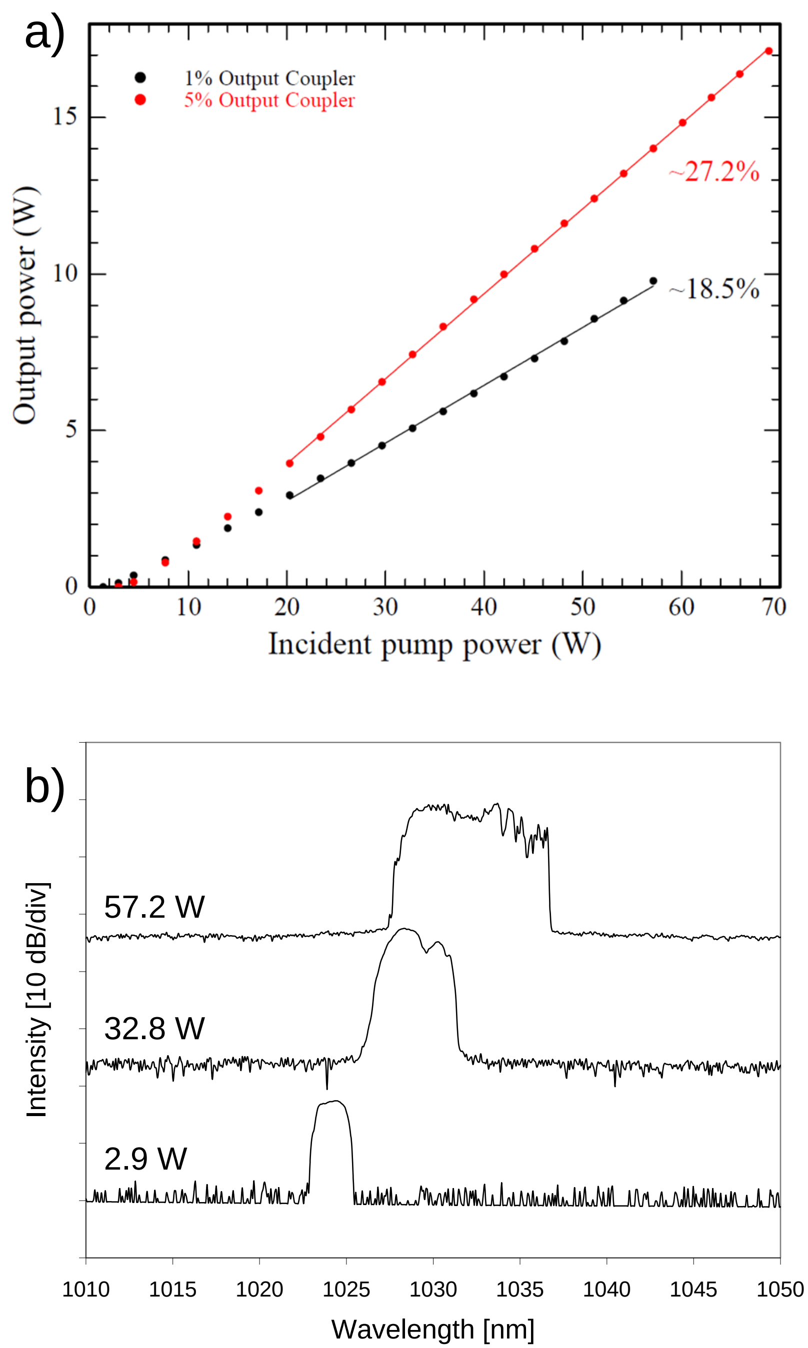
Window
laser diode
InGaAs/GaAs MQW (gain)
DBR
diamond
heat sink

Figure 3



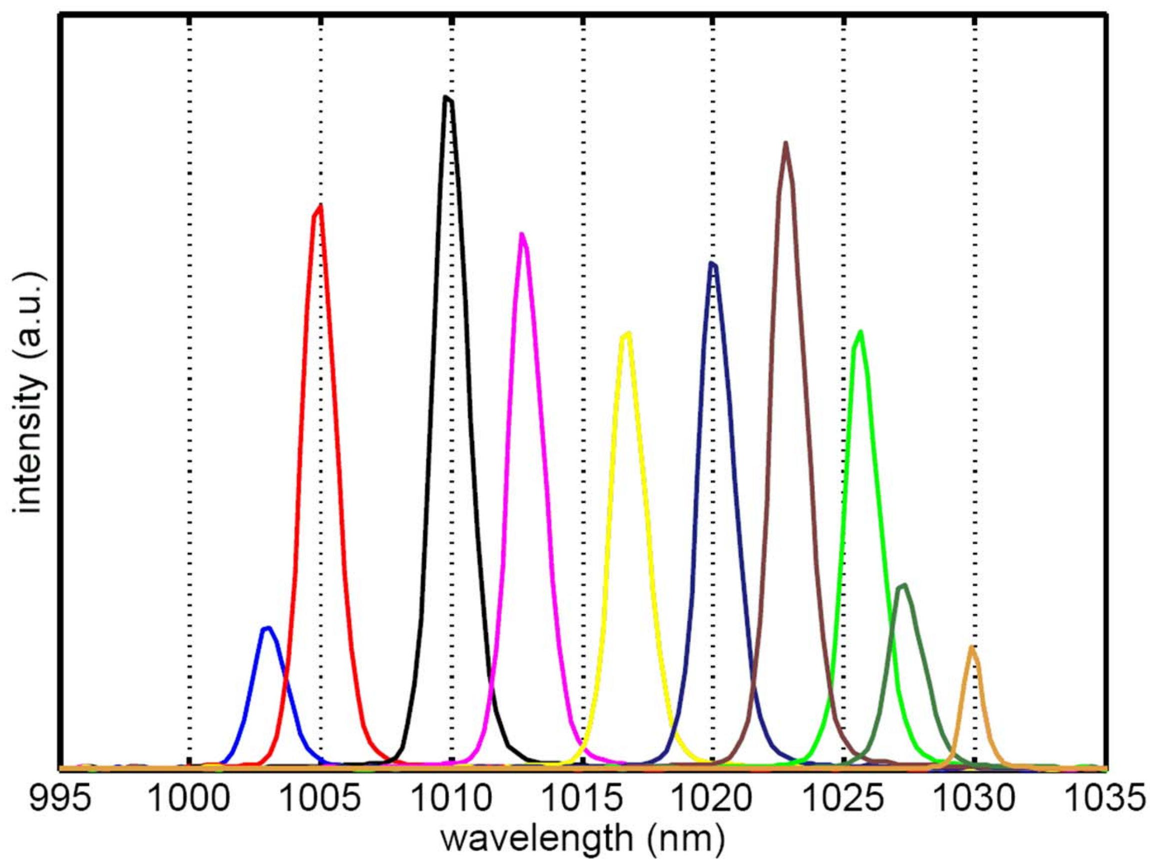
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Output Power [W]
0
2
4
6
8
10
12
14
16
18
Incident Pump Power [W]

Figure 4



a)
1% Output Coupler
5% Output Coupler
~27.2%
~18.5%
Output power (W)
0
5
10
15
0
10
20
30
40
50
60
70
Incident pump power (W)
b)
57.2 W
32.8 W
2.9 W
Intensity [10 dB/div]
1010
1015
1020
1025
1030
1035
1040
1045
1050
Wavelength [nm]

Figure 5


intensity (a.u.)
995
1000
1005
1010
1015
1020
1025
1030
1035
wavelength (nm)