Monolithic Semiconductor Mid-IR Optical Parametric Oscillators with Modal Phase Matching

R.M. Lammert, S.W. Oh, M.L. Osowski, C. Panja, P.T. Rudy, T. Stakelon and J.E. Ungar

Quintessence Photonics Corporation, 15632 Roxford Street, Sylmar, CA 91342

ABSTRACT

We present theoretical analysis and experimental data from a monolithic semiconductor laser and optical parametric oscillator device which generates near-infrared laser beam and converts it to a longer mid-infrared wavelength by modal phase matching. The device design exploits the strong optical nonlinearity and transparency of III-V compound semiconductors while achieving phase matching of the near-infrared pump beam to the mid-infrared product beam(s). These devices have the potential to dramatically improve the CW Mid-IR power available at room temperature from monolithic semiconductor lasers, making them ideal for a broad range of applications including infrared countermeasures, detecting chemical weapons, imaging, and fog-penetrating optical communications.

Keywords: Mid-IR, diode laser, semiconductor laser, eye-safe, OPO, Mid-wave

1. Introduction

Laser beams with wavelengths in the mid-infrared range between 2 and 10 um can enable a wide variety of critical defense and home and security tasks including infrared countermeasures, detecting chemical weapons, and fog-penetrating optical communications. One promising method to produce mid-infrared radiation is with optical parametric oscillators (OPOs). Optical parametric oscillation requires that the phases of the pump, idler, and product waves are matched through a nonlinear medium. Conventional techniques for phase matching in nonlinear crystals include birefringent phase matching and quasi-phase matching[1]. Until now, achieving phase matching has required the use of large OPO crystals and bulk optics since phase matching on a monolithic semiconductor chip has been impeded by the lack of birefreingence in crystals such as AlGaAs and InGaAsP. Moreover, quasi-phase matching in these crystals requires complicated processing in order to modulate the sign or strength of the nonlinear susceptibility.

We report here on semiconductor lasers which utilize modal phase matching[2] to eliminate the need for birefringence and susceptibility modulation. We utilize high power single mode near IR emitters along with the excellent nonlinear properties of GaAs, including high damage threshold and transparency in the 1-10 μm regime. Our modal phase matching approach is based on the phenomena that higher order modes in a waveguide have lower effective indices. This modal dispersion can be used to compensate material dispersion in the AlGaAs or InGaAsP crystals without complicated device processing. These devices use mature optoelectronic semiconductor material technologies, and are easily manufactured at low cost. The resulting edge emitting semiconductor laser device has unique advantages such as a nearly circular beam that is easily coupled to external optics, and an extremely high conversion efficiency .since output power increases quadratically with length of converter section.

2. Device architecture and modeling

The mid-infrared beam is created in two steps: first, near-infrared laser beams are generated, and the beam is then frequency shifted to mid-infrared by the novel on-chip nonlinear OPO. The semiconductor chip and OPO design produces the pump beam in the same waveguide that is phase matched for the near-IR pump and mid-IR product beams. This approach facilitates device compactness and also allows for simple resonance enhancement of the pump beam.

Our approach leverages the fact that higher order modes typically have lower effective refractive indices and higher phase velocities than lower order modes. We achieve phase matching of a low frequency (mid-IR) low order mode to a high frequency high order mode pump wave. Three main requirements required of the waveguide structure of the modal phase matched monolithic semiconductor OPO are: 1) modal phase matching of the near-IR pump, the idler and the mid-IR product beams, 2) sufficient spatial overlap of the near-IR pump with the idler and the mid-IR product beams, and 3) preferential lasing of the near-IR pump beam in the required higher order mode.

The first requirement is met by a simple three slab waveguide. Unfortunately, this type of waveguide results in a near zero optical field overlap of the three beams. Properly designed five slab passive waveguides[3-5] have been shown to produce modal phase matching with reasonable optical mode overlaps. The third requirement requires an active waveguide that produces a near-IR pump beam which preferentially lases in the appropriate higher order mode, which is the TE_2 mode for these devices.

Typical semiconductor waveguide structures produce a fundamental optical mode in the fast axis (TM_0 or TE_0). The InGaAs-AlGaAs shown in figure 1 simultaneously fulfills all three requirements necessary in the operation of a monolithic semiconductor OPO. This structure was designed to convert a TE_2 pump beam with a wavelength of 1 µm into a TM_0 and a TE_0 beam, both operating near a wavelength of 2 µm. The thickness and composition of the GaAs and AlGaAs layers provide an index profile which supports modal phase matching with sufficient optical spatial overlap. Figure 2 shows the calculated optical field of modes TE_2 at 1 µm and TE_0 at 2 µm. The effective indexes of these two modes are both ~ 3.2. The optical field of mode TM_0 at 2 µm is not shown but its effective index is ~3.18. The calculated normalized mode overlap (η_{OPO}) for the fast axis field distribution of the three modes is calculated to be 32%, and the intensity spatial overlap is ~10%.

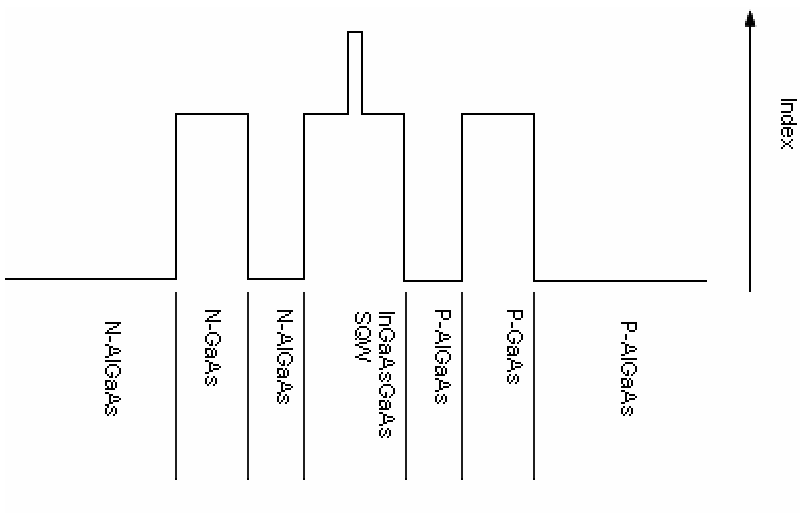

Figure 1. Modal phase matched InGaAs-AlGaAs structure.

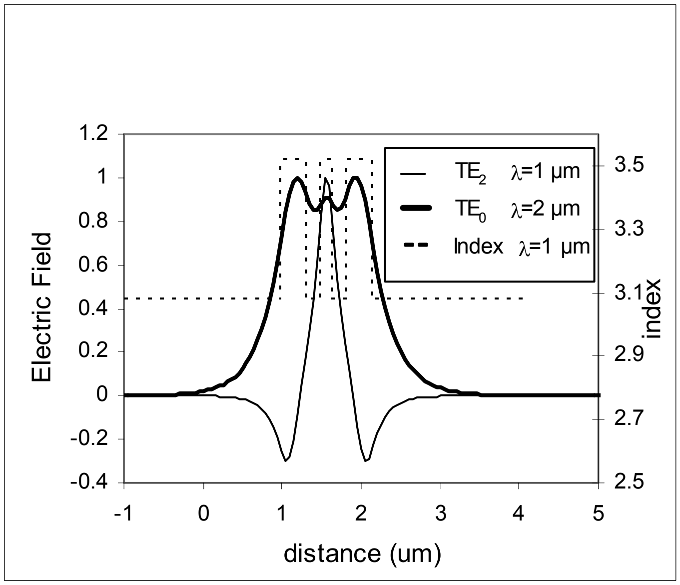

Figure 2. The calculated optical field of modes TE_2 at 1 µm and TE_0 at 2 µm

Gain to produce the near-IR pump beam is supplied by an InGaAs QW located in the center of the structure. This waveguide supports preferentially lasing in the TE_2 mode since the confinement factor and therefore modal gain is considerable higher for the TE_2 than for the TE_1 and TE_0 modes. The calculated coupling coefficients for the three confined modes at 1 µm, shown in figure 3, are 0.21%, 0%, and 4.7% for the TE_0, TE_1 and TE_2 mode, respectively.

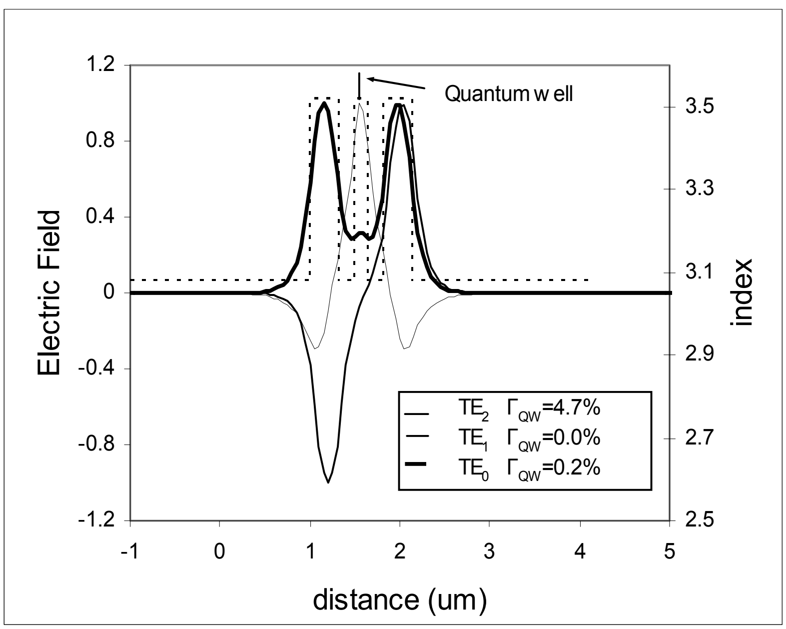

Figure 3. Calculated coupling coefficients for the three confined modes at 1 µm.

Figure 4 shows the calculated far field pattern for the TE_2 (λ = 1 µm) near field mode shown in figure 2.

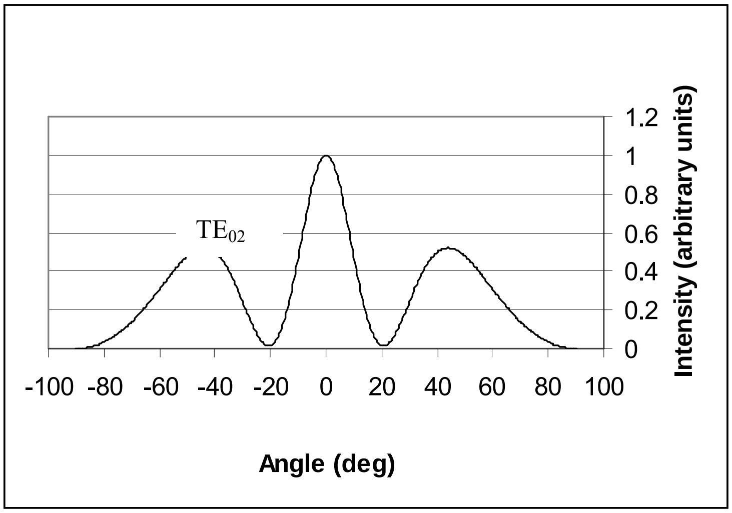

Figure 4. Calculated far field for wafer with absorption layer designed to suppress TE00.

3. Device fabrication and conversion to the sub-harmonic

We have a fabricated and characterized devices using the structure show in figure 1. The 50 µm wide, 1000 µm long cavity, broad area laser was manufactured on GaAs substrates oriented along the <011> axis. The laser devices were designed to preferentially lase in the TE_{02} mode at 1000 nm, and to phase match the fundamental to a 2000 nm TE_{00} subharmonic. With modification, very similar designs could be used to match to much longer wavelengths.

Figure 5 shows the measure fast axis far field pattern of the device at a current of 1 A. This measured far field pattern confirms the device operates in the TE_2 mode. The measured profile matches the calculated TE02 mode, and the far-field profile and optical spectrum show no measurable power in the undesired TE00 or the TE01 modes. Noise spikes are test equipment artifacts.

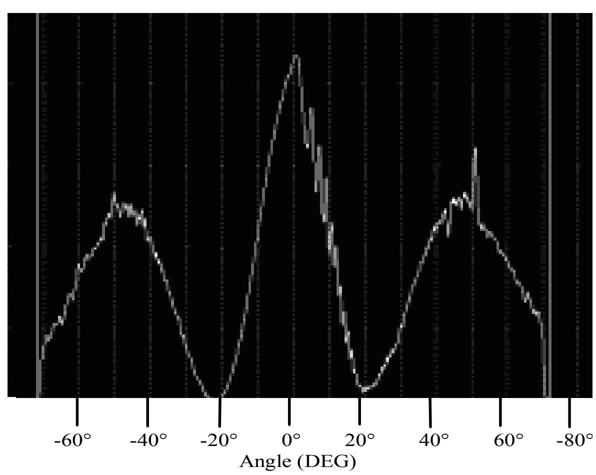

Figure 5. Measured perpendicular far field of TE00/TE01 suppressed laser.

The nonlinear gain needed to achieve OPO threshold in this structure is ~ 17 cm^{-1}. This gain is needed to overcome the losses of 5 cm^{-1} from free carrier absorption and 12 cm^{-1} from the mirrors, which is calculated assuming an uncoated facet reflectivity of 30% for the TE_0 mode at 2 µm. To achieve a nonlinear gain of 17 cm^{-1} requires an internal pump power density of 900 MW/cm^2, however application of coating with 95% reflectivity at 2 µm would reduce the required internal pump density to 50 MW/cm^2. These threshold power densities are derived using the calculated intensity spatial overlap of 10% and assuming nearly the entire pump power spectrum lies within the phase matching acceptance bandwidth. These high power densities will require high reflectivity coatings at the pump wavelength to increase the internal power though resonance enhancement.

Even though pump power densities necessary to achieve OPO threshold were not obtained, there are several indications that nonlinear processes associated to phase matching were achieved. Figure 6 shows the CW optical power versus current curve for the device. The threshold current is 75 mA and the slope efficiency is 0.25W/A per uncoated facet just above threshold.

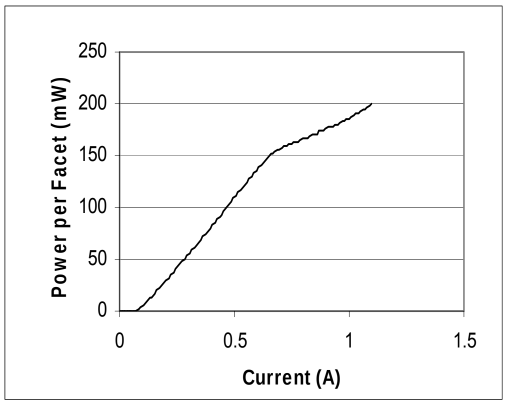

Figure 6. CW optical power versus current curve for the TE00/TE01 suppressed laser.

The kink in the L-I corresponds to an appearance of a large dip (~20 dB) in the Fabry-Perot spectra, shown in figure 6. The observed spectral behaviors are a consequence nonlinear frequency conversion and the temperature dependence of the phase-matching condition. As drive current is increased and the chip temperature increases, the dip appears, and as current is increased further, the center of this dip moves through the spectrum to longer wavelengths. At high currents, the wavelength of the dip moves beyond the longest wavelength in the spectrum, and a normal multi-mode Fabry-Perot spectrum is recovered.

This dip tunes with temperature at a rate of ~6 Å/ºC. This closely agrees with the calculated 5 Å/ºC temperature tuning of the phase matched pump wavelength. Also the spectral width of the "dip" corresponds well to the calculated phase matching acceptance bandwidth of ~2.5 nm. The L-I kink and corresponding spectral dip occurred on several wafers, one of which had a slightly modified waveguide which require the chip to operate near 100ºC before the L-I kink and spectral dip appeared. Unlike kinks seen in conventional lasers (which correspond to lateral mode shifts), the observed far-field beam patterns are identical at currents below and above the kink.

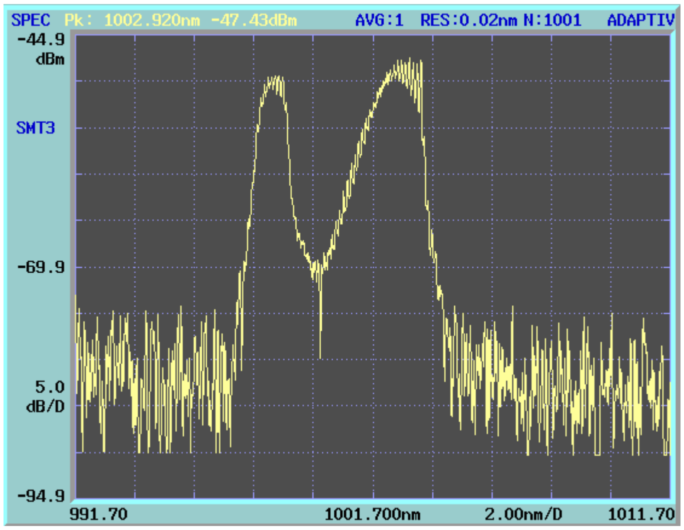

Figure 6. Optical spectrum of broad area laser designed to generate a fundamental output near 1000 nm and phase matched to the first subharmonic at 2000 nm. The spectrum shows a 20 dB dip at 998 nm, indicating power conversion from fundamental to the subharmonic.

5. Scaling the pump power

In order to achieve the OPO threshold and enhance conversion efficiency to the Mid-IR, a narrow width, high power density structure such as a ridge waveguide or buried heterostructure (BH) is required. To this end, we have developed high power single frequency, single transverse mode devices at 1550 nm.

Our device design is a two section -amplifier device consisting of two sections, a narrow waveguide section and a tapered gain section. Tapered devices have been demonstrated previously, but achieving higher power levels with near diffraction-limited performance has shown to be challenging because of filamentation at relatively low powers and poor yields due to beam quality deterioration at high powers[7-11]. In our design, the narrow waveguide distributed feedback (DFB) section, the beam is laterally confined by a single-mode waveguide which produces a single frequency stable beam with adequate intensity. The tapered element incorporates a buried heterstructure (BH) single mode waveguide which effectively acts as a mode filter. This beam is fed into the tapered gain section, where the mode is allowed to freely diffract and amplified by a tapered electrical contact. The BH single mode waveguides are ~ 1.5 µm wide and 750 µm long. The tapered gain regions are 1200 µm long and 250 µm wide at the output facet.

We have demonstrated >1.5W per emitter from 1550 nm high power, high brightness, high yield tapered lasers with single frequency and single transverse mode operation. Figure 9 shows the CW power versus current curve for a 1550 nm high power, high brightness tapered laser along with the wall-plug conversion efficiency with a constant 700mA in the oscillator section. An output power of 1.5W and a wall plug efficiency of 28% are achieved at a bias of 5A.

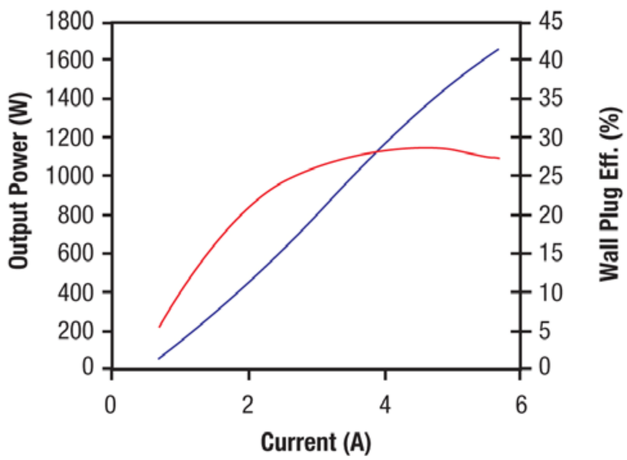

Figure 9: CW optical power versus current curve for the 1550nm TE00 single frequency laser.

Figure 10 shows the CW spectra for a device a 1W. The line width was measured to be < 6MHz, and this result is measurement limited. More than 50dB of suppression was observed.

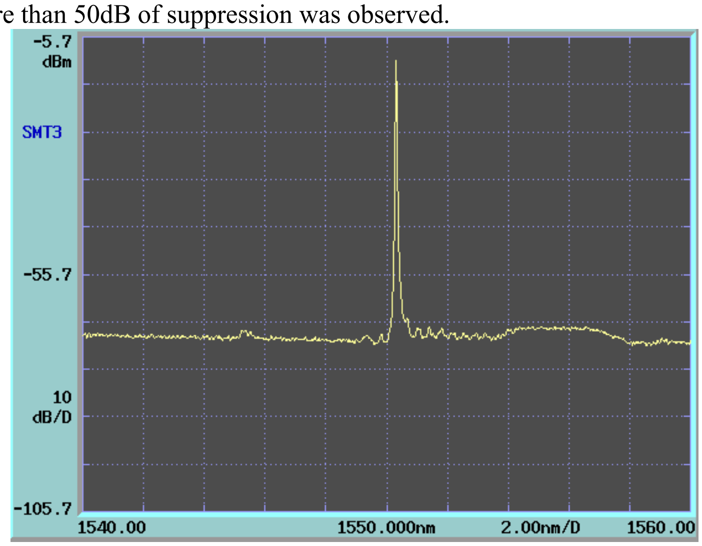

Figure 10: CW optical spectrum for the 1550nm TE00 single frequency laser.

6. Conclusions

We have designed and fabricated a semiconductor laser OPO device that achieves modal phase matching. Devices with low power density, broad area emitters show significant conversion of light from the pump beam at 1micron to its sub-harmonic at 2 micron. Additionally, we have demonstrated a 1.6W near diffraction limited single frequency 1550 nm laser which will serve as a high power density pump for future work aimed at surpassing the OPO threshold and increasing the efficiency of the conversion process. We believe that this work may enable a practical mid-infrared laser diode and represents an exciting advancement in the generation of mid-infrared laser light.

ACKNOWLEDGEMENTS

Part of this work was supported by the US Army CECOM under contract DAAB07-03-C-L415.

REFERENCES

1. S.J.B. Yoo, R. Brat et al., *Appl. Phys. Lett.*, **66,** 3410 (1995).
2. J.T. Boyd et al., *IEEE J. Quantum Electron.*, **QE-10,** 788 (1972).

3. A. Chowdhury et al., *IEEE Photon. Tech. Lett.,* **12**, 486 (2000).
4. B. Oster et al., *IEEE Photon. Tech. Lett.,* **13**, 672 (2001).
5. S.V. Rao et al., CLEO ’03, Paper CTuG1.
6. “High Reliability, High Power InGaAs/AlGaAs 980 nm Distributed Feedback Lasers with Nonabsorbing Mirrors”, Lammert, R.M., Ungar, J.E., Oh, S.W., Osowski, M.L., Bar Chaim, N., LEOS ’99, IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting vol .1 p194
7. Wolfring, B.J.; Kaenders, W.G.;
Quantum Electronics and Laser Science Conference, 1999. 23-28 May 1999 Page(s):63 – 64, “Injection-locked diode laser system delivering up to 200 mW tunable single-mode output at 685 nm”
8. Yiou, S.; Balembois, F.; Georges, P.; Huignard, J.-P.; Lasers and Electro-Optics Europe, 2003. CLEO/Europe. 2003 Conference on 22-27 June 2003 Page(s):157, “Narrow beam divergence of laser diodes with a Bragg grating in external cavity”
9. Ciapurin, I.; Smirnov, V.; Venus, G.; Glebova, L.; Rotari, E.; Glebov, L.; Lasers and Electro-Optics, 2004. (CLEO). Conference on Volume 1, 16-21 May 2004 Page(s):3 pp. vol.1, “High-power laser beam control by PTR Bragg gratings“
10. D.W. Nam et al., IEEE Photon. Tech. Lett., 5, 281 (1993).
11. J.P. Donnelly et al., IEEE Photon. Tech. Lett., 5, 747 (1993).