MID IR DIODE LASERS: STATE OF THE ART

M. TACKE

Fraunhofer-Institut fuer Physikalische Messtechnik, Heidenhofstrasse 8, D-7800 Freiburg, Germany

Abstract - A review of present mid IR diode laser achievements shows remarkable progress. cw operation temperatures above 77 K are possible now on a routine basis. Some MHz linewidth of free running lasers, good stability and single mode operation have been achieved at least with laboratory prototypes.

1. Introduction

Diode lasers for the mid IR are made of a special material, the so called lead salts or IV-VI's, like the binaries PbS, PbTe and PbSe or the ternary PbSnSe or similar semiconductors. Their main application is gas analysis by spectroscopical techniques. Systems that make use of these lasers are capable to detect polluting trace gases in the atmosphere down to sub ppb levels with a temporal resolution of the order of minutes. Laser systems can also analyze engine exhaust gases in the millisecond range, for every engine stroke separately, for CO and NO emission. These capabilities are of increasing importance and spur the laser development. This paper wants to review the relevant current laser characteristics and their future development.

2. General Laser Properties

The mid IR lead salt laser design at present follows in a way that of the near IR GaAs based lasers. These III-V lasers have seen development efforts that are incomparably larger than what could be done in the range of IV-VI diode lasers. In order to get a feeling for the difference, one can compare a $\lambda = 0.8 \mu\text{m}$ GaAs laser operating at 300 K to a PbSe active layer laser with emission near $\lambda = 8 \mu\text{m}$. Scaling the operation temperature by kT according to the wavelength, an operation temperature of 30 K results. Scaling by the wavelength is not necessarily realistic for all aspects, however it intuitively is harder for the mid IR laser to reach high temperatures. The power of standard GaAs lasers is near 10 - 100 mW with threshold currents of 30 - 100 mA, as compared to 0.1 - 0.5 mW for the IV-VI laser with threshold near 200 mA. Bearing in mind the one order of magnitude difference in quantum energy this comparison shows, that the IV-VI lasers come surprisingly close; surprising if one keeps in mind the vastly differing development activities.

The general scheme of the IV-VI lasers is shown in Fig. 1 for a stripe contact laser. All modern lasers are made by epitaxy, with MBE being at present the common technique. There are three main material families grouping around the binaries PbSe PbTe and PbS with their emission centers at $\lambda = 7.2; 4.6 \mu\text{m}$, $\lambda = 5.7; 4.1 \mu\text{m}$,

$\lambda = 4.0; 3.3 \mu\text{m}$ at 20; 80 K. In order to achieve longer wavelengths, Sn is mixed to PbSe and PbTe resulting in long wavelength lasers out to $\lambda = 30 \mu\text{m}$. The main present interest is limited to $\lambda < 15 \mu\text{m}$. For short wavelength and confinement layers Eu or Sr are admixed, and sometimes quaternarys are used for lattice matching with usually one of the neighbouring main binarys admixed in small quantities. Eu and Sr only alter the lattice periodicity length slightly, while PbS, PbSe and PbTe have quite different periodicity lengths of 5.94 Å; 6.12 Å and 6.47 Å.

Fig. 1. - Schematic of a diode laser and its resonator.

The debate on the necessity of lattice matching is still not settled. In a way this is due to the considerable scatter of individual laser data that may render a comparison difficult between lasers made in a different way and with different technology. There is evidence for stress and strain in heterostructures shifting emission wavelength in lead salt lasers. This is quite appealing, since all lead salts are multi valley semiconductors, and the "right" strain might thus reduce threshold currents by a factor of four. Generally, the material system is quite forgiving due to the high static dielectric constants that screen crystal faults. The IV-VI semiconductors are generally quite soft, but mechanical deformations do not seem to effect laser properties severely. In general, this material system is manageable with simple techniques and quite stable. This is not unexpected bearing in mind that the first diodes for communication use were made from naturally grown PbS one century ago.

Returning to Fig. 1, it is worth while to mention that there are still no reflection coatings used for the resonators. The facet reflection of more than $R = 0.4$ is sufficient for most purposes, but the two sided emission is a disadvantage since the backward beam is at present commonly not used and may be a source of uncontrolled feedback. Hence in calculating the threshold gain g_{th}

$$g_{th} = \frac{1}{2L} \ln \frac{1}{R_1 R_2} + \alpha$$

the first term giving the reflection losses is comparable for most lasers and with a typical length of $L = 0.3 \mu\text{m}$ and $R_1 = R_2 = 0.44$ amounts to 27 cm^{-1} . A problem not encountered in near IR lasers is the high absorption constant α due to free carrier absorption. As an example, an active layer of PbSe at threshold at 77 K will have more than 10 cm^{-1} absorption solely by this process, and the losses in a highly doped confinement PbEuSe layer may be well above 100 cm^{-1} . This may lead to a threshold gain of more than 50 cm^{-1} for the whole mode. The problem is reduced at shorter wavelengths since the free carrier absorption is proportional to λ^2 , but it is increased as one leaves the binary active material since the ternaries have reduced electron mobilities.

Fig. 2 shows typical I/U and P/I diagrams of a good heterostructure stripe contact laser. The increases in series resistance with temperature are due to the temperature dependence of the carrier mobilities and unavoidable. They are one reason for limiting cw currents to max. 1 A in stripe contact lasers. The output power goes into several modes, the efficiency decreases markedly as one reaches 200 K.

Near 80 K, one can take an external differential efficiency near 2 % from this Figure. With $\alpha = 50 \text{ cm}^{-1}$ and $g_{th} = 74 \text{ cm}^{-1}$ this results in an internal quantum efficiency

of 8 %. Even singular lasers of this type do not exceed 4 %, so there is ample room for improvement. This seems to be typical for all MBE heterostructure lasers reported in the literature. Diffused homostructure lasers offer better efficiencies so these values are not limited by the material, and one has to bear in mind the 50 % efficiency that Shinotara et al. reported for a well designed PbSnTe active layer double heterostructure made by LPE and optimized for efficiency. Modern MBE lasers reach higher operation temperatures and thus justify the concentration on this type of epitaxy, but obviously more technological development is still needed.

Fig. 2. - Current/voltage and power/current characteristics of a DH laser for several temperatures.

The maximum operation temperatures of PbSe based lasers are shown in Fig. 3. The highest operation temperatures above 170 K were observed with the binary. Similar qualitative temperature ranges were found for the other compounds PbTe and PbS, each centered around a maximum at the respective material wavelength near 170 K for stripe contact lasers. Higher operation temperatures were observed with lateral structures described in the next section.

Fig. 3. - The maximum cw operation temperatures reported for DH lasers peaks for PbSe based compounds near 6 μm with PbSe active material. The open dot shows data for PbS, the closed dot for PbTe active laser (3, 5, 6).

The wavelength span of such lasers is large, as seen in Fig. 4. In pulsed mode, the lasers can withstand high currents. Some spectroscopic techniques can be used with pulses and are now possible above 200 K for active materials near the binaries, hence thermoelectric cooled operation is possible and was already demonstrated.

Fig. 4. - The threshold current and tuning range of DH lasers with PbSe active material that reached 174 K cw (3) and 17 $^{\circ}\text{C}$ (4) in pulsed mode.

3. Microstructures

Lasers made of homostructure diodes are still used and fabricated, since this technology is well established and quite dependable. The need for high operation temperatures and better control of the modal properties has however shifted the

research and development activities completely to lasers made by heteroepitaxy and photolithography.

By variation of the crystal growth, the lasers are structured perpendicular to the surface. The standard structure is made by growing an active layer of 0.5 to 1 μm thickness between two cladding layers of a material with larger bandgap. By introduction of such double heterostructures (DH) made by MBE, D. Partin was able to reach cw operation temperatures close to 150 K in 1983 (1). DH lasers are now state of the art, and basis for modern designs. Further transverse structuring with narrow active layers, quantum wells, resulted in increased operation temperatures of 175 K (D.L. Partin (2), 1984). Due to lack of material knowledge, the design of quantum well lasers was (and still is) difficult. Hence this promising transverse structure has seen less development effort for the IV-VI lasers and still offers potential improvement for the maximum operation temperatures that now reached 175 K for the binary active layer DH lasers.

As to the debate on the necessary lattice match of these heterostructures: There is close but not perfect lattice match between the binaries PbSe and PbTe and the corresponding wider band gap PbEuSe and PbEuTe ternaries. Making heterostructures of these materials will result in material stress and/or dislocations at or near the heterointerfaces. By going to quaternary material, in principle a perfect match is possible. This route has been followed e. g. for PbTe and PbEuSeTe (e. g. (1, 2, 5, 6)). Minimum threshold currents of 3.9 A/cm² at 15 K were reported for lattice matched DH lasers (7). The best non lattice matched PbSe/PbEuSe lasers showed 60 A/cm² at 20 K (8), the difference may be due to the mismatch.

The technological question of whether perfect lattice match is necessary is still not settled. Interface recombination generally is assumed to be independent of temperature. Hence at high temperatures with current densities of kA/cm² the mismatch induced current loss should be negligible. Moreover, material stress changes the semiconductor band structure (9) and has proven to be favourable for III-V heterostructure devices. It is typical that even such basic questions are still open and hence leave ample room for improvements due to the comparably limited effort that can be put into the IV-VI laser research and development.

The most simple lateral structure is a striped contact. Due to the limited stripe width, some 20 μm , the current is laterally concentrated and results in an active volume width somewhat larger than the stripe width. The actual effective width that results is hard to estimate, moreover it fluctuates due to current filamentation and due to changes of the optical modes. The weak structural definition of the active width results in the frequent coexistence of different lateral modes and mode fluctuations, both highly unwanted for spectroscopic applications.

The most straightforward remedy is a lateral confinement by etching Mesa structures, see Fig. 5. Such Mesas can be made down to some micrometers wide (8). There are two disadvantages to this lateral structure: due to the large step of the refractive index at the Mesa sides, lateral multimode operation is possible for moderate width. Small widths are technologically undesired on the other hand, since they result in mechanical instability.

Fig. 5. - Different lateral geometries.

At present, the generally favored lateral structure consists of an active layer which has stripe shape and is embedded in cladding material, the so called buried heterostructure lasers (see Fig. 5). This design is well known for advanced III-V Lasers and has been used with success for the IV-VI lasers as well (10, 11, 6). The most recent results reported 1991 by Z. Feit et al. (6) showed an increase in cw operation temperature to 203 K and good mode behavior. This increase in operation temperature range is due to the lateral structure superimposed to the basic DH structure.

Microstructures are also used along the propagation direction. Periodic corrugations are used in DBR (distributed Bragg reflector) and DFB (distributed feedback) lasers to enforce operation in single longitudinal modes. The feasibility of such structures has been demonstrated for IV-VI lasers (12). Current effort is in improvement of their tuning, which has been demonstrated e.g. by a separate contacting to two segmented lasers (13). One of the segments can be thought to provide the necessary gain, the other to mainly tune the emission. The periodic structures are mature on a laboratory basis and must now be developed to the prototype stage.

4. Radiation Properties

Output power is a basic laser parameter. Typically, a IV-VI laser will deliver less than 1 mW. The quantum efficiency does not seem to depend markedly on the laser wavelength, hence one can expect more power at the shorter than at the longer wavelength. In pulsed operation or at high cw currents, 1 mW may well be exceeded, and up to 10 mW multimode emission has been observed. For gas analysis applications, high output power generally is not a predominant issue and thus currently is not a major development goal. This may change in the future, since the high sensitivity frequency modulated spectroscopy techniques ask for milliwatt power levels in single modes. A point that did not get sufficient attention is the spatial distribution into which the laser power is emitted. The commonly observed uneven radiation patterns are not suited for high sensitivity applications; there is need for improvement of the laser designs.

Linewidth, stability and amplitude noise are crucial for high resolution spectroscopy applications. Laser intensity noise is the ultimate limitation for all techniques that rely on intensity measurements. Noise properties are thus getting renewed interest. The laser noise theoretically shows a descent with increasing current, and should be white if quantum limited. Experimental data show a fast roll off at low frequencies [14]. This low frequency noise reaches out well above 10 kHz and is one to two orders of magnitude larger than the following high frequency noise. It is not easily interpreted and probably due to optical feedback, at least to a large extent. Moreover, it seems to be strongly specimen dependent.

The high frequency noise is not white as well, but also goes down with frequency [15]. This $1/f$ type behaviour has been observed in different laser structures, and is an order of magnitude larger than a theoretical estimate [16]. Present state of the art laser diodes can allow noise to power ratios down to 10^{-8} (into 1 Hz bandwidth) in limited temperature and current areas. One of the reasons for the development of lateral structures is their potential low intensity noise within a large operation parameter range.

Aside from the amplitude noise, frequency fluctuations are detrimental for many diode laser applications. In general, the frequency bandwidth of the IV-VI lasers seems to be well explained by a small linewidth of a few MHz that jitters within a larger band. The smaller high frequency short term linewidth seems to be due to noise mechanisms of the laser itself, while experiments showed the lower frequency jitter to depend strongly on external influences due to the power supply and cooler.

A bandwidth of some MHz, which probably can be achieved routinely with improved design will be sufficient for most applications. It can be reduced by external resonators, but this route is not followed with great emphasis at present, since present applications do not ask for more than this order of magnitude.

5. Conclusions

Compared to the III-V lasers of the near infrared, the mid IR diode lasers are obviously less developed. They lack the financial background of large quantity use and production. Comparing, one should keep in mind that the IV-VI lasers are judged by their typical users due to their demand for very low noise, and a necessary relative mode frequency stability of some 10^{-6} over long periods, that the typical III-V laser would not be able to fulfill. In view of the vastly different research and development efforts that went into these two laser families, the mid IR IV-VI lasers surely need not hide. There is however still room for improvement.

The author is grateful for the collaboration of his colleagues at the IPM, and open discussions with others working in the field.

References

- [1] PARTIN, D.L., Appl. Phys. Lett. 43 (1983) 996.
- [2] PARTIN, D.L., Appl. Phys. Lett. 45 (1984) 487.
- [3] TACKE, M., SPANGER, Beate, LAMBRECHT, A., NORTON, P., BÖTTNER, H., Appl. Phys. Lett. 53 (1988) 2260.
- [4] SPANGER, Beate, SCHIESSL, U., LAMBRECHT, A., BÖTTNER, H., TACKE, M., Appl. Phys. Lett. 53 (1988) 2582.
- [5] FEIT, Z., WOODS, R., KOSTYK, D., JELANETZ, W., Appl. Phys. Lett. 55 (1989) 16.
- [6] ISHIDA, A., MURAMATSU, K., TAKASHIBA, H., FUJIYASU, H., Appl. Phys. Lett. 55 (1989) 430.
- [7] FEIT, Z., KOSTYK, D., WOODS, R.J., MAK, P., Appl. Phys. Lett. 58 (1991) 343.
- [8] FEIT, Z., WOODS, R., KOSTYK, D., JALENAK, W., Appl. Phys. Lett. 55 (1989) 16.
- [9] SCHLERETH, K.H., BÖTTNER, H., TACKE, M., Appl. Phys. Lett. 56 (1990) 1269.
- [10] BÖTTNER, H., SCHIESSL, U., TACKE, M., Superlattices and Microstructures 7 (1990) 97.
- [11] SCHLERETH, K.H., SPANGER, Beate, BÖTTNER, H., LAMBRECHT, A., TACKE, M., Infrared Phys. 30 (1990) 449.
- [12] FEIT, Z., KOSTYK, D., WOODS, R.J., MAK, P., Appl. Phys. Lett. 57 (1990) 2891.
- [13] SHANI, Y., KATZIR, A., TACKE, M., PREIER, H., IEEE J. Quantum Electron. QE-25 (1989) 1828.
- [14] SCHLERETH, K.H., Diodenlaser mit verteilter Rückkopplung für das mittlere Infrarot, Ph.D. Thesis, Würzburg (1990).
- [15] FISCHER, H., WOLF, H., HALFORD, B., TACKE, M., Infrared Physics, to be published.
- [16] WERLE, P., SLEMR, F., GEHRTZ, M., Appl. Opt. 28 (1989) 1638.
- [17] FISCHER, H., TACKE, M., JOSA B, to be published.
- [18] LAMBRECHT, U., FISCHER, H., RIEDEL, W.J., WOLF, H., TACKE, M., submitted for publication.