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Direct Solar Pumping of Semiconductor Lasers: A Feasibility Study

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1. Introduction

This report describes results of NASA Grant NAG-1-1148, entitled *Direct Solar Pumping of Semiconductor Lasers: A Feasibility Study*. The goals of this study were to provide a preliminary assessment of the feasibility of pumping semiconductor lasers in space with directly focused sunlight and to identify semiconductor laser structures expected to operate at the lowest possible focusing intensities. It should be emphasized that the structures under consideration would provide direct optical-to-optical conversion of sunlight into laser light in a single crystal, in contrast to a configuration consisting of a solar cell or storage battery electrically pumping a current injection laser. With external modulation, such lasers could perhaps be efficient sources for intersatellite communications. We proposed specifically to develop a theoretical model of semiconductor quantum-well lasers photopumped by a broadband source, test it against existing experimental data where possible, and apply it to estimating solar pumping requirements and identifying optimum structures for operation at low pump intensities. These tasks have been accomplished, as described in this report of our completed project.

The report is organized as follows: Some general considerations relevant to the solar-pumped semiconductor laser problem are discussed in Section 2, and the types of structures chosen for specific investigation are described. The details of the laser model we developed for this work are then outlined in Section 3. In Section 4, results of our study are presented, including designs for optimum lattice-matched and strained-layer solar-pumped quantum-well lasers and threshold pumping estimates for these structures. It was hoped at the outset of this work that structures could be identified which could be expected to operate continuiously at solar photoexcitation intensities of several thousand suns, and this indeed turned out to be the case as described in this section. Our project is summarized in Section 5, and information on publications resulting from this work is provided in Section 6.

2. General Considerations

The sun is a very non-ideal pumping source for semiconductor lasers. The total power density available in the AM0 solar spectrum is 135 mW/cm^2, only one-half to three-quarters of which is available in the form of photons energetic enough to generate electron-hole pairs in common semiconductors materials. Preliminary calculations described in our original proposal suggested that even with high efficiency conversion of incident photons into electron-hole pairs in the laser active region, solar magnifications of a few thousand suns would yield pair generation rates at the lower end of what is required to drive the lowest threshold semiconductor lasers. It was thus expected at the outset that, while potentially feasible, solar-pumped semiconductor lasers would have to make very efficient use solar spectrum and be capable of operation at very low pump powers.

The requirement for low-threshold pump power density immediately suggested the use of some suitably modified and optimized version of a separate-confinement quantum-well heterostructure (SC-QWH) laser. These lasers combine the superior gain properties of ultrathin (<500Å) quantum-well active layers with the superior waveguiding properties achievable using thicker (>1000Å) active regions, resulting in operation at extremely low thresholds. A schematic cross section of a "step-index" SC-QWH laser is shown in Fig. 1 along with a band-gap profile for the structure. Ignoring the substrate, which plays no role in the laser operation, the structure is constructed from multiple layers of three different semiconductor materials with different band gap energies. High-gap cladding layers surround a medium-gap waveguide region, the center of which is punctuated by one or more low-gap quantum-well layers. For a typical photopumped structure, the surface cladding layer is thick enough to absorb most of the (usually monochromatic) pump light, but thin enough so that most of the photogenerated electrons and holes diffuse to the waveguide region without recombining (typically ~1 μm). Once in the waveguide region, virtually all of the carriers become trapped within the thin quantum well layers, where they remain confined until they recombine. The photons generated from radiative quantum-well recombination are efficiently guided along the waveguide layer, the thickness of which is usually chosen to optimize confinement of the optical mode (typically ~1000Å) and thus insure a strong interaction between the light field and carriers confined to the quantum well. It is the ability to separately design the waveguide and quantum-well regions for optimum optical and carrier confinement, respectively, that gives SC-QWH lasers both their name and their capability for low-threshold operation. For this reason, and since the use of the multiple band-gap layers offered potential benifits in making optimum use of the solar spectrum, suitably designed SC-QWH lasers appeared most likely to operate at low solar concentrations and were thus the exclusive focus of our study.

We expected the design of solar-pumped SC-QWH lasers to involve a variety of trade-offs and compromises, since material combinations and structure dimensions which minimize lasing thresholds can not be expected to coincide with those which maximize efficient use of the solar spectrum. Given that the usable power available at reasonable solar concentrations is so close to expected best-case lasing thresholds, and that the number of relevant design parameters is so large, we expected that a somewhat detailed theoretical analysis would be required to identify even the most important design trade-offs. Indeed, some trends and features of the optimum structures were shown by detailed analysis to be quite the opposite of what we expected initially, as will be discussed later in Section 4. At this point, however, the structure of the quantum-well laser model developed for this work will now be described.

3. Solar-Pumped Quantum-Well Laser Model

Becuase of their continued proven capability to provide low-threshold operation, step-index SCQWH lasers with a single quantum well (cf. Fig.1) were studied exclusively. The incident solar radiation at air-mass zero (AM0) was modeled as a 5800K blackbody characterized by an integrated power density of 135 mW/cm^2 before focusing. Electron-hole pair generation throughout the solar-pumped laser structure was obtained from wavelength-dependent absorption coefficients for the cladding and waveguide layers and from the thicknesses of these layers. Transport of carriers generated in the top cladding layer to the waveguide region was treated using an ambipolar diffusion model including recombination at the cladding layer surface, which was checked for accuracy using more involved numerical calculations. All carriers reaching the lower-gap waveguide layer were assumed to be captured in that layer. Furthermore, all carriers reaching the waveguide region from the cladding layers *and* all carriers generated within the waveguide layer itself were assumed to become uniformly distributed throughout the waveguide region. The assumption of uniform spatial distribution was introduced primarily to simply calculations of quasi-fermi levels, which were assumed constant throughout the waveguide region with this entire region charge neutral. It should be noted that the bottom cladding layer turned out to play an insignificant role in the absorption of sunlight, since all photons with energies larger than the waveguide region band gap were found to be absorbed in the top cladding layer and waveguide region for structures of suitable dimensions for solar-pumped operation.

The model of the laser active region, which was formulated to treat both strained and unstrained quantum wells, requires more detailed discussion. Energies and envelope functions for the quantized energy states in the quantum well were determined using a standard finitie potential well model with appropriate boundary conditions. Strain-dependent effective masses along directions perpendicuar to the quantum well were used, and band nonparbolicities were included. The effects of band mixing on effective masses in the plane of the quantum-well layer was, however, ignored. Quasi-fermi levels were obtained by assuming a staircase quasi-two dimensional density of states in the well region and a three-dimensional density of states in the surrounding waveguide region, and by assuming equal integrated electron and hole populations in entire waveguide/quantum-well region as mentioned earlier. Standard treatments of emission, absorption, and gain in the quantum well region were employed, with transition matrix elements obtained using a k·p-based treatment which includes effects of quantization and non-unity overlap of electron and hole envelope functions. Broadening of the gain function was treated using a lineshape function which included both homogeneous and inhomogeneous components. A transfer matrix approach was used to calculate the distribution of electromagnetic energy in the waveguide region, and thus to obtain the optical confinement factor specifying the fraction of light in the laser cavity available to participate in optical feedback. Non-radiative recombination (including Auger recombination), free-carrier absorption, and scattering losses were treated using typical values and/or semi-empirical models. Thicknesses of strained quantum wells examined were never greater than 70% of predicted critical thicknesses for dislocation formation to insure that only realizable structures of high crystalline quality would be considered.

We expect that the main factors limiting the accuracy of our model are (*i*) the neglect of rather complex effects such as band mixing and (*ii*) the unavoidable problem of being unable to precisely know lineshape functions, cavity losses, non-radiative recombination, and other parameters which can be specific to material quality in individual devices. Again, we have used typical values for these parameters and have attempted to be conservative wherever possible. We do not expect errors incurred by these factors to be sufficiently large, however, to preclude our obtaining meaningful estimates of optimum parameters for solar-pumped laser operation. Several comparisons were made to assess the accuracy of our model for lasers fabricated from the well established and commonly used AlGaAs-GaAs semiconductor system. We modified our model to treat injection lasers and compared predictions from our model against recent data for single-well AlGaAs-GaAs SCQWH laser diodes (*J. Appl. Phys.* **68**, 1964 (1990)). Absolute values for threshold currents were predicted to within a factor of about 1.3, and the predicted structure dependence of threshold current agreed well with experiment as well. In Fig. 2, predicted results for the dependence of threshold current on waveguide Al composition (solid curve) are shown with the experimental data (data points) for 800μm-long laser diodes. Encouraged by these results, we applied our model to the determination of optimum structures for solar-pumped laser operation.

4. Results

An optimization routine was used to find the optimum compositions and thicknesses for the quantum-well, waveguide, and upper cladding layers of single-quantum well SCQWH laser structures. The common lattice-matched $Al_zGa_{1-z}As$-$Al_yGa_{1-y}As$-GaAs (z>y) system was studied, as was the highly successful and now widely studied strained-layer $Al_zGa_{1-z}As$-$Al_yGa_{1-y}As$-$In_xGa_{1-x}As$ system. Aluminum compositions only as high as 0.8 were considered, as wavelength-dependent absorption coefficients were not available for z>0.8, and a lower limit of 0.1μm for the cladding layer thickness was imposed. All calculations were for 800μm-long cavities at T=300K, and the aluminum composition of the bottom cladding layer was set to z=0.85. Results of the optimization runs for both types of structures are shown in Fig. 3. Optimum parameters for the various layers are given, as are predicted solar concentrations (in AM0 suns) for the optimum structures. (Parameters labeled by an * were driven to their limits during optimization.) Note that the strained-layer structure is predicted to offer a three-fold reduction in threshold solar magnification due to the lower-gap materials which are used in the structure (hence better use of the solar spectrum) and the superior properties of strained-layer active regions. Note also that the optimum lattice-matched $Al_zGa_{1-z}As$-$Al_yGa_{1-y}As$-GaAs structure was obtained by optimizing with respect to five design parameters, which is one parameter less than required for the strained-layer structure since the quantum-well material is a binary compound rather than a ternary alloy.

The primary quantitative conclusion of these results is that solar-pumped semiconductor laser operation should indeed be achievable at solar concentrations on the order of thousands of suns, particularly if strained-layer quantum-well active regions are used. The most surprising qualitative conclusion is that maximum use of the solar spectrum is best achieved through the use of an unexpectedly thick waveguide region, with the upper cladding layer playing a nearly insignificant role in solar absorption. Waveguide thicknesses in the optimum solar-pumped structures are roughly twice as thick as those which optimize optical confinement in injection lasers, allowing for increased absorption of the above-gap incident photons in the solar pumped structure but lowering the optical confinement factor. The trade-off is illustrated in Fig. 4, which shows the variation in the threshold magnification with waveguide layer thickness for the optimum lattice matched structure. With most absorption occurring in the waveguide, the optimum cladding composition is driven toward large values and the cladding layer thickness toward small values. This decreases absorption in the cladding region and helps to confine light to the waveguide region. Optimum designs for solar-pumped structures thus turn out to be qualitatively different from those for injection lasers, and are so for reasons which could be revealed only through a somewhat detailed analysis such as the one carried out here.

5. Summary

The feasibility of directly photoexciting semiconductor lasers with focussed sunlight was investigated theoretically, and it was concluded that photopumped operation should be possible at AM0 magnifications of several thousand suns in properly designed structures. Since the use of semiconductor laser structures well suited for low-threshold operation will likely be required to achieve operation at such magnifications, we considered step-index single-quantum-well SCQWH lasers and identified optimum parameters for minimum threshold under solar photoexcitation. A relatively detailed laser model was developed for this purpose, and used to design and evaluate optimum lattice-matched AlGaAs-GaAs and strained AlGaAs-InGaAs based structures. Threshold magnifications for the optimum strained structures (~2500 suns) were predicted to be roughly three times lower than those for the lattice matched lasers (~8000 suns). Parametric studies were performed to identify the effects of various structural parameters on solar-pumped laser operation. Compared to single-well SCQWH current-injection lasers, structures optimized for direct solar photopumping were found to require relatively thick waveguide regions and relatively thin surface cladding layers with large band gaps.

6. Publications

Results from this work have been or will be reported in three documents:

1. Our early results for the lattice-matched structures were presented at the IEEE Summer Topical Meeting on Spaceborne Photonics in Newport Beach, California in July 1991. Our talk is summarized in:

   Sreenath Unnikrishnan and Neal. G. Anderson, "AlGaAs-GaAs Quantum-Well Lasers for Direct Solar Photopumping", *1991 IEEE Summer Topical Meetings Digest*, p. 88, IEEE, New York, 1991.

   A copy of this paper is appended to this report.

2. The project is summarized in the M.S. thesis:

Sreenath Unnikrishnan, "Solar Pumped Semiconductor Lasers for Space Communication Applications - A Feasibility Study," M.S. Thesis, University of Massachusetts at Amherst, February 1992.

A copy of this thesis can be provided upon request.

3. Results of the entire project will be reported in the literature in:

Sreenath Unnikrishnan and Neal G. Anderson, "Quantum-Well Laser Structures for Direct Solar Photopumping," in preparation for early summer submission to *IEEE Journal of Quantum Electronics.*

Copies of this paper will be forward to NASA immediately upon completion.

Figures

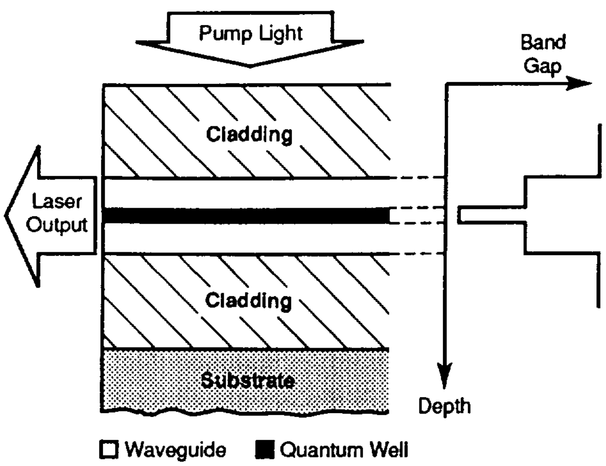

Figure 1

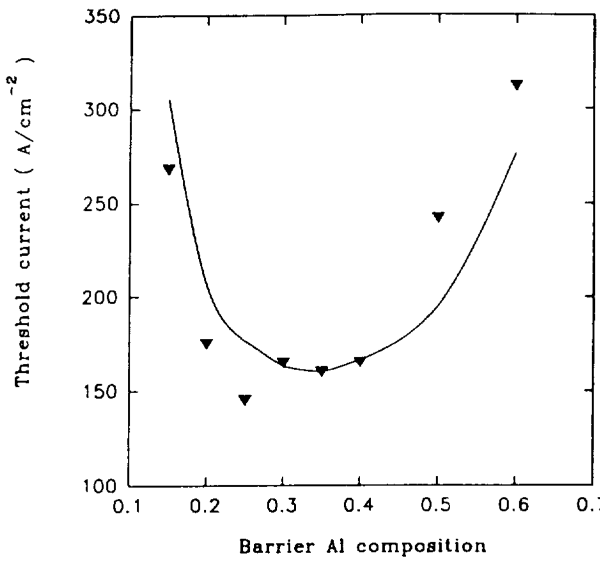

Figure 2

Variable	Optimum	
	unstrained	strained
Well *In* composition (x)	0.0	0.33
Well width	51A	55A
Waveguide width	0.18 μm	0.20 μm
Waveguide *Al* (y) composition	0.32	0.00
Cladding *Al* (x) composition	0.80 *	0.65
Cladding layer thickness	0.100 * μm	0.20 μm
Minimized Concentration	8060	2500

Figure 3

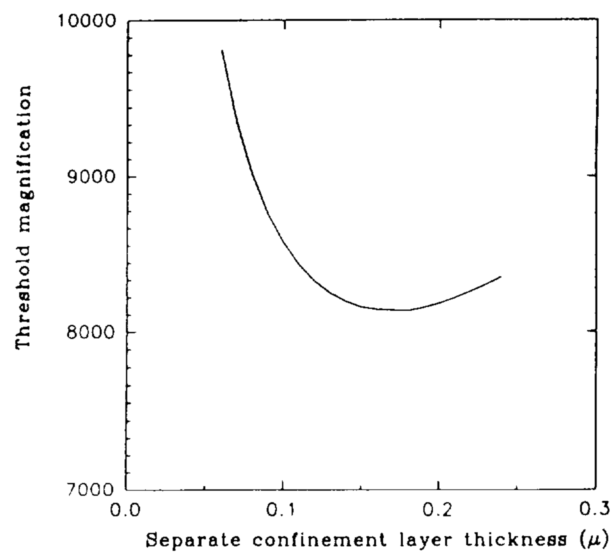

Figure 4