

Prospects for Solar Pumped Semiconductor Lasers

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Abstract

Approaches are discussed for a direct solar-pumped semiconductor laser. Efficiencies of 35% should be achievable, an order of magnitude better than the efficiency achieved by other solar-pumped lasers. The output wavelength of a semiconductor laser will be well matched to the optimum conversion efficiency of a solar cell of the same material. Solar pumped semiconductor lasers are thus an excellent candidate for space-based energy transmission. Recently several designs for such lasers[1-3] have been proposed.

A critical parameter is the sunlight intensity required for lasing. This threshold has been calculated to be in the range of 2500 to 10,000 times solar intensity for conventional stripe laser designs, depending on assumptions. Several approaches have been recently proposed to reduce this threshold. The calculated minimum threshold is 25-50 times solar concentration, and could possibly be reduced even further with use of light-trapping.

1. INTRODUCTION

There has recently been increasing interest in the possibility of using beamed power for space applications [4-6]. There are several advantages of lasers over other techniques of beamed power. The receiver for laser beamed power is a solar array, and so no new receiver technology is needed. Optimized for a fixed laser wavelength, photovoltaic cells can achieve over 50% efficiency [7]. The short wavelengths of laser radiation means that the receivers and transmitter apertures can be quite small. Hence, laser power transmission can be feasible for comparatively small scale systems.

Some applications of interest include powering a lunar base during the lunar night, powering remote rovers on the surface of the moon and Mars, powering systems in Earth orbit, and providing power to an electric-propulsion orbital transfer vehicle.

The biggest hurdle to the use of laser power beaming is the laser itself. The difficulties of beaming power from space are weight and efficiency. A free-electron laser requires a linear electron accelerator and a long wiggler section of alternating magnets. Such a system would be too massive to consider for a space-based system. An alternative often discussed is the semiconductor laser diode. Laser diodes have relatively high efficiency (about 50% DC to laser power) and are inherently lightweight. Further, the output wavelength of 800 to 900 nm is very close to the peak response wavelength for existing solar cells.

A diode-based system typical of those proposed uses a solar panel to provide electricity, which is fed into a power conditioning system and then operates the diode laser. While the solar cell efficiency may be as high as 30% if the best laboratory cells are used, 15% efficiency is more typical of that flown in space today. Accounting for 80% efficiency in power conditioning and transmission and 50% laser efficiency, the total system efficiency is expected to be on the order of 6%.

Several researchers have investigated lasers powered directly from solar energy. Such a system is known as a "direct solar-pumped laser." Successful solar pumped Nd:YAG and Nd:Cr lasers have been demonstrated with power levels up to 25 watts, and iodine lasers at up to 10 watts [8]. The wavelength of these lasers (1.06 μ for Nd:YAG; 1.31 for I) is slightly too long for use with existing solar cells. The power conversion efficiency is very low. For Nd:YAG, 2.4% slope has been efficiency observed, and 6% predicted as theoretically possible. For iodine lasers, solar to laser power efficiency of about 0.5% is expected [9]. In addition to the low efficiencies, the wavelength produced by these lasers is slightly too long to be efficiently converted to electricity by photovoltaic receivers.

An alternate approach is to use solar energy to directly pump a semiconductor laser. The system of using a gallium arsenide solar cell to power a gallium arsenide laser is inherently redundant: why not do both functions in the same piece of gallium arsenide? Since the operating wavelength of a semiconductor diode laser is by necessity near the bandgap wavelength of the material, the output wavelength is very nearly that at which a diode of the same composition will best converts light into electricity.

The advantage of higher efficiency for power-beaming applications, is that the size of the concentrator mirror can be considerably reduced. For a 1MW output power, for example, a YAG solar pumped laser operating at 6% efficiency would require a 125 meter diameter circular mirror to concentrate sunlight sufficiently for operation. Such a mirror size, larger than a football field, is well beyond anything currently projected for space operation. At 0.5% efficiency, a 430 meter diameter would be required. At 35% efficiency, on the other hand, a mirror of only 52 meter diameter would be sufficient. While such a mirror is still considerably larger than anything that has been currently launched into space, it is possible that such a solar concentrating dish could be constructed by use of an inflatable structure. Since semiconductor lasers are inherently of low power, it is more likely that a power of a megawatt would be achieved with a large number of smaller mirrors; for example, an array of 10,000 half-meter diameter dishes. Such a mirror size is practical with current technology.

2. SOLAR PUMPED SEMICONDUCTOR LASERS

A solar cell uses a p-n junction operating in reverse bias to collect electron-hole pairs created by light. A diode laser uses a p-n junction operating in forward bias to inject electron-hole pairs into a semiconductor to create light. In principle, there is no reason why the electron-hole pairs created by sunlight cannot be directly used as the excited medium for a laser.

A semiconductor material has a great advantage over other laser systems for direct solar pumping. Most lasers, such as the Nd:YAG discussed above, absorb light only in selected bands. This leads to inefficient absorption of the broad-band solar spectrum. A semiconductor, on the other hand, absorbs all photons with energy greater than the bandgap. Thus, solar-pumped semiconductor lasers could have considerably higher efficiencies than other solar-pumped lasers.

A solar pumped laser would be subject to the same losses as a solar cell, and the efficiency of a solar-pumped GaAs laser should be about 35%. This is an order of magnitude better than the few percent efficiency achieved by other solar-pumped lasers, either directly or indirectly pumped.

For stimulated emission to occur, the population of the energy levels of the laser must contain a population inversion. This requires a very high injection level. The parameter of interest is the threshold intensity, the minimum intensity of the pumping light required to achieve lasing. Here we will measure this in terms of the required optical concentration in units of multiples of solar intensity; that is, the amount by which Air Mass Zero (AM0) sunlight must be concentrated to achieve lasing. AM0 sunlight is assumed to have an intensity of 137 mW/cm². Sunlight has a wide spread of photon energies, some of which will be in the infrared at wavelengths too long to be absorbed, and others at wavelengths which are not effectively used by the material. Hence, the required intensity for optical pumping using sunlight will, in general, be higher than that required for optical pumping using a more optimal wavelength.

3. CONVENTIONAL STRIPE STRUCTURES

In 1992, Tsidulko [1] and Landis [2] separately published discussions of direct solar-pumped semiconductor lasers, using as a basis design parameters for electrically-pumped GaAs lasers. They both considered use of a wide-bandgap absorber material to clad a narrow stripe of active material, in order to achieve concentration of electron-hole pairs, and arrived at similar results for the required threshold concentration. Shortly thereafter, Unnikrishnan and Anderson [3] published a calculation of the minimum threshold concentration required for direct solar pumping, basing their calculation on first-principles rather than from existing laser results.

Threshold calculations from each of these are shown in table 1.

Table 1:
Calculated Threshold Solar Concentration for Solar Pumped Semiconductor Diode Lasers

<i>Calculated Threshold Concentration for Conventional Designs</i>		
Tsidulko [1]	2500 suns	AlGaAs/GaAs
Landis [2]	3000 to 10,000 suns	AlGaAs/GaAs
Unnikrishnan & Anderson [3]	8060 suns	AlGaAs/GaAs
<i>Calculated Threshold Concentration for Advanced Designs</i>		
Unnikrishnan & Anderson [3]	2500 suns	AlGaAs/InGaAs strained
Tsidulko [1]	25 suns	Graded bandgap to concentrate pairs
Landis [2] revised (see discussion)	250-1000 suns	Cladding material to concentrate pairs
	10 to 30 suns	above plus light trapping

Tsidulko and Landis both calculated threshold solar intensity which would be required if lasers of existing design were pumped by solar, rather than optical or electrical, means. The laser operation is shown in figure 1. Tsidulko calculates the required threshold intensity by extrapolating from quoted results of an argon-ion pumped AlGaAs/GaAs laser, which achieved threshold at about 170 W/cm². Since solar pumping is less efficient than laser pumping, this corresponds to a threshold of about 2500 suns. Landis calculates from the threshold current of existing semiconductor diode lasers, by assuming that in a solar-pumped laser each absorbed photon creates one electron-hole pair, and then compares this result with quoted results of optically pumped semiconductor lasers in a manner similar to that of Tsidulko. The minimum threshold current for existing semiconductor lasers is under 300 A/cm², and under 100 A/cm² has been reported in the laboratory. Since the photocurrent at AM0 for a GaAs solar cell is about 30 mA/cm², the concentration of sunlight required to produce lasing thus ranges from 10,000 suns (for 300 A/cm² threshold) to 3000 suns (for 100 A/cm² threshold). The lower value corresponds well to the value calculated by Tsidulko.

Unnikrishnan and Anderson take a different approach, and calculate directly from electronic band properties of the materials. Their design uses two layers of AlGaAs cladding, which should be expected to concentrate carriers in a fashion similar to the "advanced" design of Landis. However, since they do only a one-dimensional analysis, lateral concentration of carriers is not modeled. They then go on to optimize their parameters for layer thickness and bandgap. Their best calculated threshold of about 8000 suns for an AlGaAs laser is comfortably in the range of 2500 to 10000 suns analyzed by Landis, although somewhat higher than the 2500 suns calculated by Tsidulko.

In summary, use of conventional designs can be expected to achieve solar-pumped threshold at optical concentrations between 2500 and 10000 times AM0 solar intensity. Such intensities, although not beyond the limits of technology, are too high for practical solar-pumped lasers. It is

no wonder that little research is being done to make solar-pumped semiconductor lasers. If nothing else, since semiconductor lasers must operate at temperatures near or below room temperature (20°C), the difficulty of removing waste heat from the structure would be significant. It is thus of great interest to consider approaches which could reduce this threshold.

4. ADVANCED LASER DESIGNS

Unnikrishnan and Anderson then discuss the possibility of decreasing the required threshold intensity by decreasing the bandgap of the active material by using an InGaAs strained layer to replace the GaAs active layer. By removing the requirement for a lattice-matched structure, the bandgap is lowered, and hence a larger portion of the solar spectrum can be utilized, at the price of an increase in the wavelength of the light. Landis also briefly discusses use of materials in the InGaAlAsP system, without calculating threshold improvements. Unnikrishnan and Anderson find an optimum at a bandgap of 0.97 eV, corresponding to a wavelength of about 1.27 microns. This wavelength, unfortunately, is slightly too long to be easily utilized by photovoltaic cells, and hence this approach will probably not be useful for power beaming applications.

Tsidulko and Landis consider the effect of reducing the threshold intensity by designing a structure in which carriers are funneled into the active region using a variation in bandgap.

Landis, assuming carriers move only by diffusion, calculates that carriers generated in the wider bandgap region can be collected by a narrow bandgap active stripe.

Figure 2 shows the cross section of the structure, in the simplest form. The active GaAs material is a stripe of material surrounded by the absorbing $\text{Ga}_x\text{Al}_{(1-x)}\text{As}$, which is surrounded by confining layer of AlAs. This material can be grown by the process of metal-organic chemical vapor deposition. Figure 3 shows this as a semiconductor band diagram. The reference suggests that an enhancement of the concentration of photogenerated carriers by a factor of 40 could be achieved [2]. This concentration is, however, perhaps optimistic. A revision of this calculation, taking into account the fact that vertical concentration of electrons is already assumed in the baseline case, suggests that this approach will only concentrate electrons by at most a factor of 10. Hence, the revised threshold intensity is expected to be in the range of 250 to 1000 suns.

Tsidulko calculates that a graded bandgap can concentrate the photogenerated electron-hole pairs by as much as a factor of 100, using the bandgap gradient to enhance the diffusion of carriers to the active stripe. A graded bandgap has often been proposed as a method to enhance the efficiency of GaAs solar cells, but to date has not resulted in improved efficiency. The structure proposed is shown in figure 4. The bandgap is a maximum at the hemispherical surface (1), and minimum at the active stripe (3) at the bottom. The bandgap gradient thus directs generated minority carriers downward, and the tapered walls (of wide-bandgap AlAs) confine the carriers into an ever narrowing region. The design also incorporates an integral lens in the AlGaAs material. In principle, he suggests this can reduce the threshold to as low as 25 suns intensity.

Landis goes on to suggest an additional method to decrease threshold intensity, use of a "light trapping" structure. This effectively concentrates the light intensity within the semiconductor to values higher than the external concentration. It is possible to increase the

average path length of a ray of light inside a semiconductor to a $4n^2$ times the thickness of the material [10,11], where n is the refractive index (about 2.9 for AlAs). One structure for light trapping is the cross-grooved structure shown in figure 5 [11,12]. This could be made either in a surface emitting or an edge-emitting configuration. If this structure is made from aluminum arsenide (AlAs), it will be transparent to the solar wavelengths of interest. Theoretically, this could increase the effective intensity at the laser region by a factor of 34, and hence reduce the required (external) concentration by the same amount. This reduces the threshold to 10 to 30 suns.

For lasers in stripe configuration, the dimension of the optical output would be about one micron, and hence the beam would be highly divergent due to diffraction. Additional output optics would be needed to reduce the divergence and to combine the output from many elements into a single beam. The highest power density of a semiconductor laser is on the order of 4 MW/cm²; leading to a maximum power per stripe of about 40 mW. This means that for power beaming applications, it would be necessary to have a large number of individual elements, which must be coherently phased to produce a single beam. This is a difficult, but not impossible, problem.

Figure 6 shows an alternative structure, a surface-emitting laser with an external Fabry-Perot cavity rather than an integral cavity. There are advantages to this configuration for high-power output levels [13] and also for coherent phasing of many laser elements. Separate front and rear mirrors, as shown, allow easy alignment for testing. A production laser would likely have a metallized back surface instead of a back mirror. There are several approaches to configuring the system for surface emission. Figure 7 shows a detail of the laser structure. Again, the collection area is much larger than the emission area, allowing the threshold to be decreased. Since this configuration concentrates carriers in two dimensions, it could potentially have as much as 100 times lower threshold intensity than conventional stripe geometries.

5. CONCLUSIONS

A solar-pumped laser using a semiconductor as the lasing material should allow efficiencies approaching 35% to be achieved at a wavelength near that of optimum conversion efficiency by photovoltaic cells. Innovative designs are discussed which allow the laser threshold to be achieved at solar intensities easily achievable with existing solar concentrators.

6. REFERENCES

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Figure Captions

1. Solar pumped semiconductor laser operating in conventional "stripe" configuration.
2. Structure of solar pumped semiconductor laser.
3. Energy band diagram of solar-pumped double heterostructure semiconductor laser
4. Structure proposed by Tsidulko.
5. Solar pumped semiconductor laser configured using a light-trapping structure to increase the effective concentration at the active region.
6. Solar pumped laser configured as a surface emitting laser with external optical cavity.
7. Surface-pumped semiconductor laser configured using separate laser platelets.

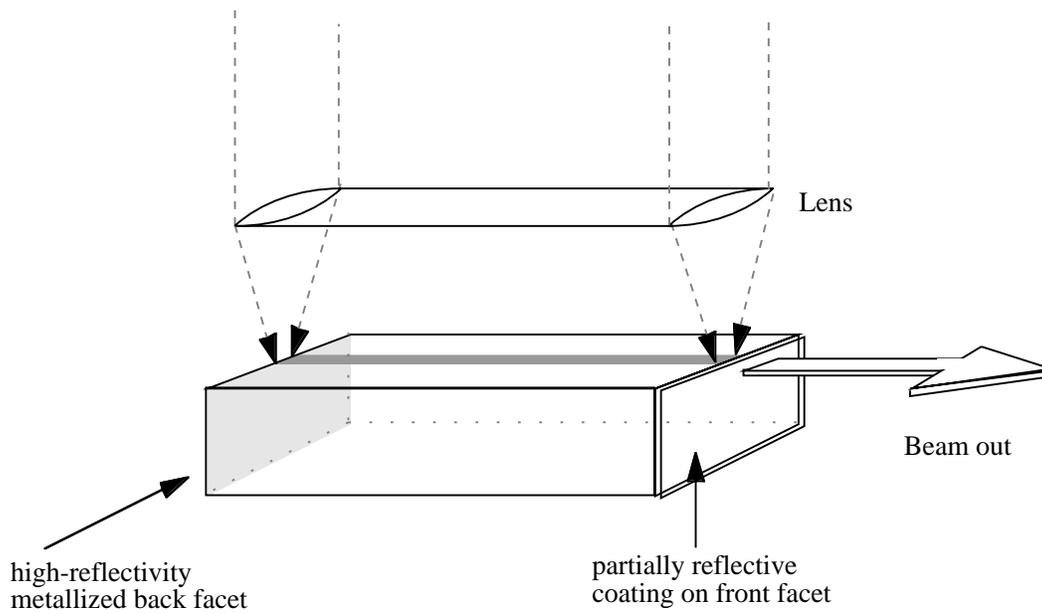


Figure 1: Solar pumped semiconductor laser operating in conventional “stripe” configuration.

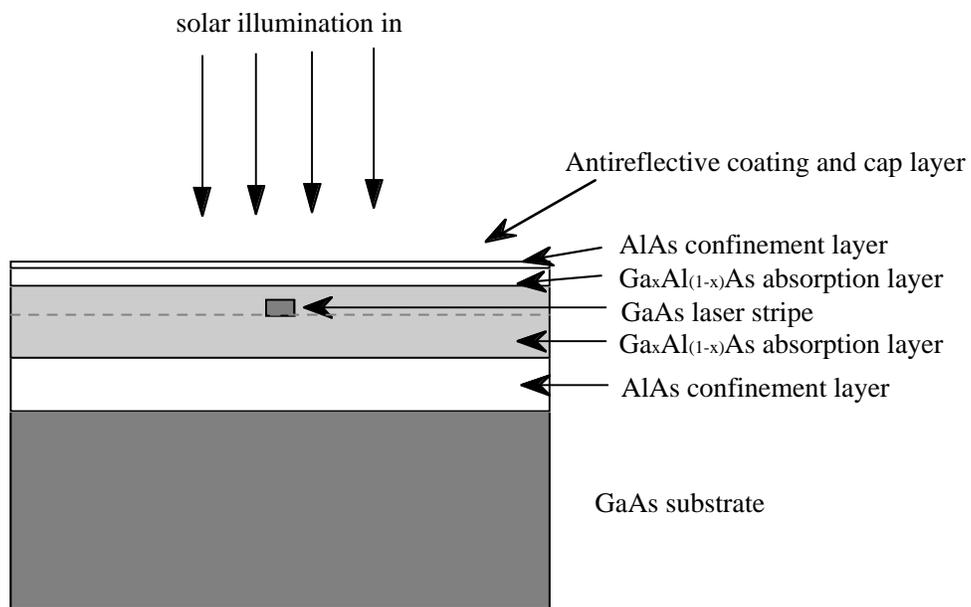


Figure 2: Structure of solar pumped semiconductor laser.

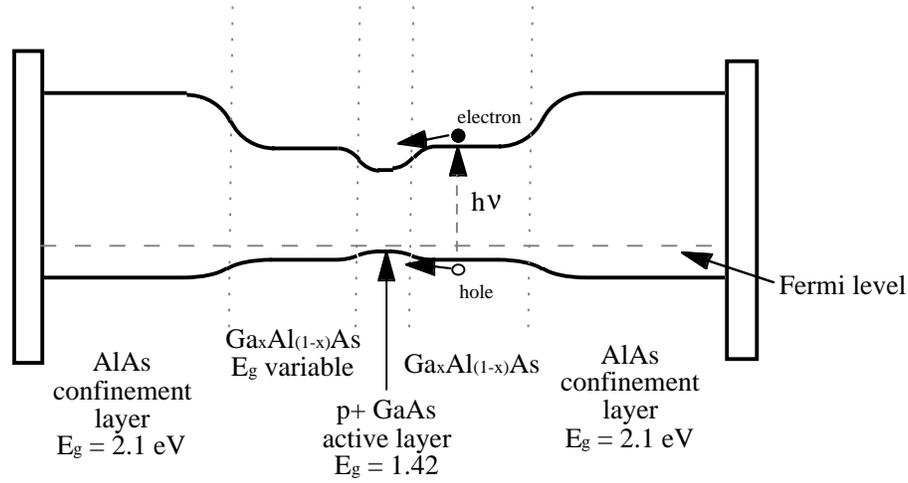


Figure 3: Energy band diagram of solar-pumped double heterostructure semiconductor laser

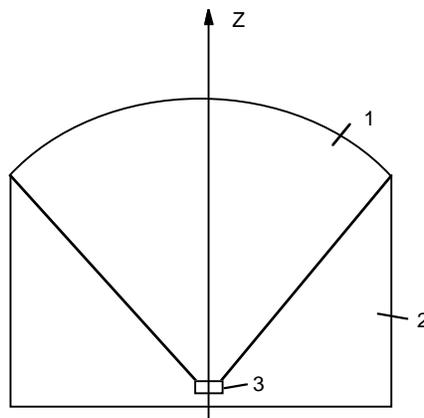


Figure 4: Solar-pumped AlGaAs/GaAs laser proposed by Tsidulko [1]. Bandgap of AlGaAs is widest at the surface (labelled 1) and narrowest at the active stripe (3).

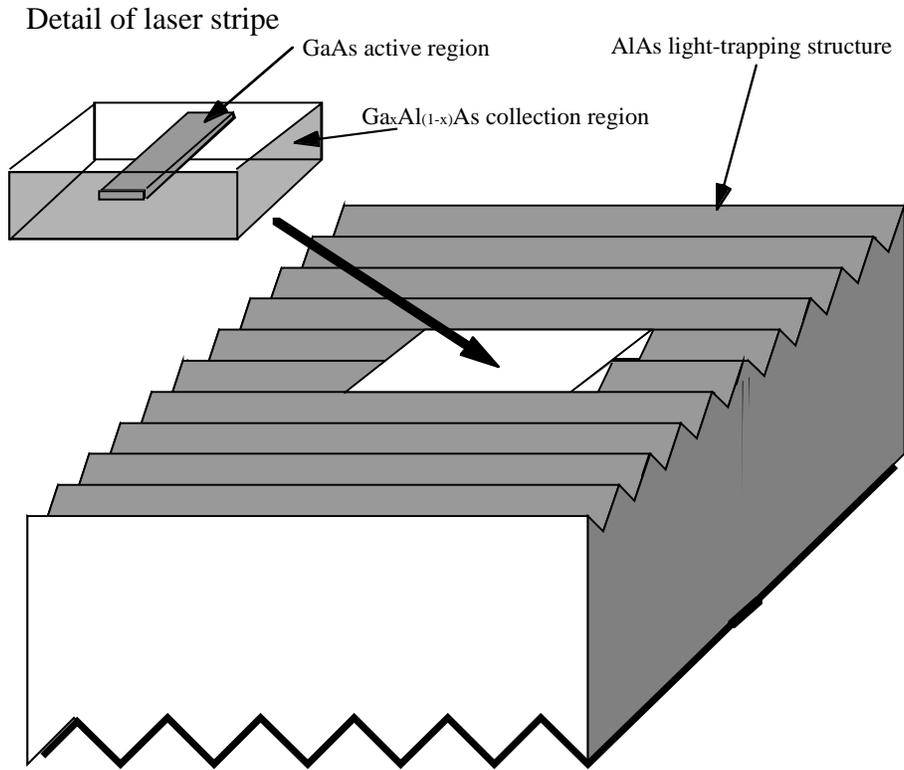


Figure 5: Solar pumped semiconductor laser configured using a light-trapping structure to increase the effective concentration at the active region.

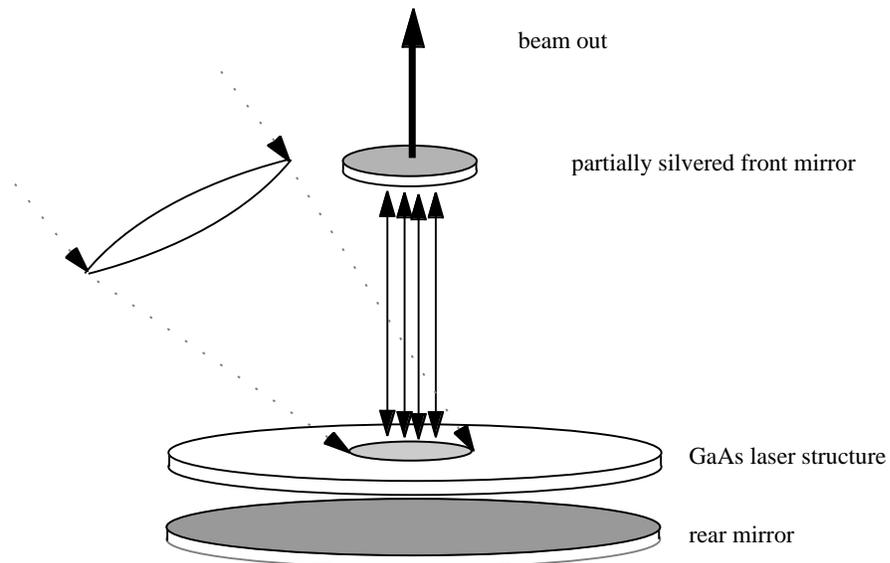


Figure 6: Solar pumped laser configured as a surface emitting laser with external optical cavity.

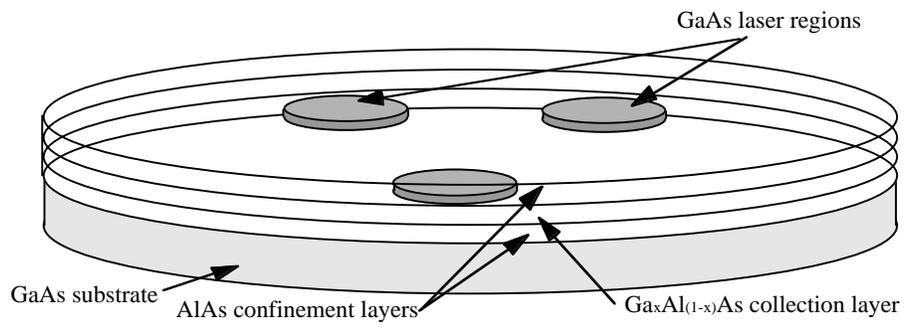


Figure 7: Surface-pumped semiconductor laser configured using separate laser platelets.