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Item Type	text; Proceedings
Authors	Katz, Joseph
Publisher	International Foundation for Telemetering
Journal	International Telemetering Conference Proceedings
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Download date	22/08/2022 18:50:36
Link to Item	http://hdl.handle.net/10150/612883

SEMICONDUCTOR OPTOELECTRONIC DEVICES FOR FREE SPACE OPTICAL COMMUNICATIONS

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ABSTRACT

Light emitting devices based on AlGaAs lasers are very useful radiation sources in free space optical communications systems. After a brief review of the properties of individual injection lasers, more complex devices are described. These include, or are relevant to, monolithic integration configurations of the lasers with their electronic driving circuitry, power combining methods of semiconductor lasers, and electronic methods of steering the radiation patterns of semiconductor lasers and laser arrays. Fabrication of such devices is one of the major prerequisites for realizing the full potential advantages of free space optical communications.

I. INTRODUCTION

One of the main prerequisites for realizing all of the potential advantages of free space optical communications is the fabrication of light sources possessing high efficiency and brightness combined with long lifetimes. In this paper we will review existing and proposed light emitting devices based on AlGaAs laser technology [1]. These devices include the semiconductor injection lasers themselves, their monolithic integration with electronic driving circuitry, laser arrays and electronically beam steerable lasers and laser arrays. The reasons for considering these devices for this application is explained in a later section. Briefly we can say that from the combined aspects of reliability, efficiency, small size and weight and ease of modulation, semiconductor injection lasers are far better than any other laser existing today. Due to the vast market of optical printers, discs and fiber links, they also have the most mature technology among all the other lasers.

The outline of this paper is as follows. The basic characteristics of semiconductor injection lasers are briefly reviewed in Section II, with special emphasis on the advantages of using them in optical communication systems. The monolithic integration of these lasers with their electronic drivers (both bipolar and FET types) is described in Section III. Monolithic integration is motivated by the need to achieve higher reliability, lower cost and faster temporal response. Section IV describes several methods for overcoming the main drawback of this type of laser, namely, its inability to emit the needed amount of optical power in a single mode operation. These methods are based on the operation of arrays of semiconductor injection lasers, usually with some phase-locking mechanism. Finally, Section V addresses the problem of electronic implementation of beem steering. Beam steering is obviously needed for free space communication systems with their beam pointing tracking and acqusition subsystems. A considerable reduction in the size and weight of the optical transmitter, as well as increased reliability, are expected if at least some of the functions which traditionally are done mechanically are monolithically incorporated with the light emitting device itself – either single lasers or laser arrays.

II. SEMICONDUCTOR INJECTION LASERS

One of the major prerequisites for realizing all of the potential advantages of optical communications in space applications is the existence of technologically mature and operationally adequate radiation sources in the visible/infrared regime of the spectrum.

At the present time, the most viable candidate for this application is the semiconductor injection laser, and specifically those lasers fabricated of the AlGaAs ternary system [1]. This type of laser emits light in the 0.8 - 0.9 µm wavelength region and has the inherent advantages of overall high efficiency (>30%), small size, and the ruggedness and reliability of solid state devices. Operating lifetimes in excess of ten years at room temperatures have been projected from accelerated life tests [2]. Furthermore, such devices are capable of being modulated at rates up to the GHz region [3]. Another desirable characteristic of these lasers is that for a given output light power, their overall efficiency increases as the temperature is reduced. Since in a spacecraft it is possible, in principle, to achieve passive (radiative) cooling, a considerable reduction of emitter primary power can be expected.

As seen in Fig. 1, the semiconductor laser is, in its most basic form, a p-n junction that emits coherent light when the current passing through it exceeds a certain value called the threshold current, I_{th} (see Fig. 2). The light emitted for currents lower than the threshold current is weak and incoherent. The magnitude of the threshold current itself depends on the particular laser parameters (typical values correspond to current densities of about 1 kA/cm^2).

The main drawback of this type of laser comes from the fact that for space applications, the laser is required to emit its light in a well behaved radiation pattern and spectral distribution. In order to fulfill this requirement, it is necessary to limit the cross-section of the emitting region of the laser (called the active region) to dimensions of the order of several wavelengths. Since due to material limitations the maximum laser intensity cannot exceed a certain level, a single laser cannot supply all of the required power. Furthermore, these material properties also place limitations on the available peak power, which in turn restrict the class of modulation formats that the laser can be used with. Best lasers demonstrated so far emit in excess of 50 mW in a single mode CW operation [4] and several hundred milliwatts peak power in a low duty cycle operation. Some methods of achieving more power via the combined operation of several lasers are described in Section IV.

III. INTEGRATED OPTOELECTRONIC CIRCUITS

In virtually all the applications envisaged for the semiconductor injection laser, its light output is to be modulated. One of the main advantages of the semiconductor injection laser is that its light output can be modulated by controlling the current passing through it. This current modulation is usually accomplished by connecting the laser to some electronic driving circuitry, to which the input modulation signal (usually at low power levels) is supplied. In most of the systems in use today, the laser and its driving circuitry are fabricated on different substrates, or “chips”. There are potential advantages in combining all these functions monolithically on a common substrate. All other things being equal, the monolithically integrated device will be simpler to fabricate, will have higher reliability and higher speed compared to the same circuit mode of discrete devices.

Fortunately, the AlGaAs ternary system has properties which makes it a suitable candidate for fabricating both electronic and optical devices. Compared to silicon, the backbone of the electronic industry today, GaAs is a direct bandgap material, so efficient light generating processes are possible in it, and the charge carriers have higher mobilities and shorter lifetimes.

Pioneering work in the area of integration of lasers with AlGaAs Metal-Semiconductor-Field-Effect-Transistors (MESFETs) was performed by Yariv and his co-workers [5],[6]. The two devices were connected in series, and the drain current of the MESFET (controlled by an external voltage) modulated the laser. Recently, in a more advanced version of this integrated circuit, a modulation capability exceeding 4 GHz has been demonstrated [7].

Although FETs are somewhat faster than bipolar transistors, it is also possible to fabricate the latter with cutoff frequencies well within the GHz regime [8]. In addition, the ultimate limit on the frequency response of the combined circuit is likely to be imposed by the laser diode itself and not necessarily by the driving circuitry [9]. Other practical arguments in favor of using heterojunction bipolar transistors (HBT) are that they are easier to interface with conventional digital circuitry, and they possess very high current gains. Devices which combine on a single GaAs substrate the operation of a HBT with a laser have been demonstrated. The circuit diagram is shown in Fig. 3. Again, the two devices are connected in series, and the collector current of the HBT is used to modulate the laser.

A schematic lateral cross section of one of the devices is shown in Fig. 4 [10]. The laser used was fabricated with a beryllium implanted stripe [11]. The HBT, which has the same structure as the laser (the only difference in the functioning of the devices was obtained by connecting them differently) achieved common emitter current gains in excess of 900. The integrated combination, nicknamed a "translaser" has been modulated at rates as high as 300 megahertz. Recently, another version of a bipolar transistor using a better laser structure has also been demonstrated [12].

The examples of optoelectronic integrated circuits described above serve to demonstrate the prospects of future optical communications systems with significantly improved characteristics.

IV. POWER COMBINING OF SEMICONDUCTOR LASERS

In this section we describe several methods of combining the power of several semiconductor lasers, thus solving the problem of insufficient power that can be delivered by one laser in a single mode operation. The power combining can be done coherently [13] - [17] or noncoherently [18] - [20]. Coherent power combining, via phase-locking of the lasers, has several advantages over noncoherent power combining. First, when the power of the lasers is combined incoherently, each laser emits light in its own individual spectrum. Thus it is necessary to have an optical filter with a wider bandwidth at the receiver, at the expense of increased detected background noise radiation. Secondly, the locking of the lasers causes a reduction in the far field divergence angle in a similar fashion to microwave phased antenna arrays. This makes the task of subsequent beam narrowing simpler (e.g., by requiring an optical telescope with a smaller magnification). As will be described in the next section, coherent power combining also makes monolithic realizations of beam steering of the laser array possible.

There are three main methods for coherent power combining, namely mutual coupling, injection locking and amplification. Schematic configurations of these methods are shown in Fig. 5. The common feature of all these methods is the establishment of some coherent interaction between all the elements of the array.

In the case of mutual coupling (Fig. 5a), no laser in the array has a privileged status. There is a certain amount of coupling among the laser (due to their fields overlapping), which, under certain conditions, results in their synchronization. This method has been analyzed [21] and demonstrated [13] - [17]. The requirements for maintaining phase locking among the lasers in the array is quite stringent. Roughly speaking, the intrinsic frequencies of oscillation of the individual lasers must be maintained within a very close proximity of each other, typically within a relative deviation of a few ppm.

Injection locking of lasers (Fig. 5b) is obtained by similar physical mechanisms. In this case, however, there is a master laser oscillator. Portions of its emitted radiation are coupled simultaneously into all the other lasers in the array, forcing them to oscillate at its frequency. There is no coupling among the lasers in the array and no coupling from the array back into the master laser. Injection locking was analyzed in electrical oscillators [22] and in lasers [23], and has been experimentally demonstrated in lasers [24]. The locking range is comparable to that of mutual coupling configurations.

Coherent amplification (Fig.5c) is similar to injection locking: in both cases there is a master laser-oscillator. However, in the case of coherent amplification, the elements of the array are only gain elements (i.e., amplifiers) without feedback. (This is accomplished by coating the lasers' mirrors with anti-reflection coating, thus eliminating their feedback mechanism.) Light generated in the master-oscillator is split and fed simultaneously into all the gain elements, where a traveling-wave amplification is employed. The amplified outputs of the amplifiers are automatically phase-locked (provided, of course, that the output of the master oscillator is coherent over the extent of its light emitting facet) and this is the main advantage of this method. Amplification in semiconductor materials has been analyzed [25], and the operation of coherently amplified GaAs homojunction devices has been demonstrated [20].

The three methods are comparable from the aspects of overall power efficiency and the need of additional optical components (e.g., phase shifters in tandem with each laser). The mutual coupling approach is potentially more reliable (since the performance of the entire array can, in principle, be designed in such a way that it is not critically affected by a failure of a single element) and more amenable to monolithic implementation (because of its more symmetrical configurations). However, from the point of view of thermal considerations and two-dimensional realizations (which is important for achieving reduction of the far-field pattern of the array in both directions), arrays based on injection locking or on coherent amplification are preferable.

Before concluding this section it is important to note that the choice of the optimum method depends on the overall system parameters. Since there is no single coherent power combining method with decided advantages over the others, a detailed comparison between the coherent power combining methods has to be carried out in any case of a particular system design. However, all other things being equal, it seems that the coherent power amplification is somewhat better than the other methods, delivering essentially the same performance without having to satisfy the additional and rather stringent requirement for synchronization of two (or more) oscillators. It should also be noted that although incoherent power combining is easier to implement, the significant advantages offered by coherent power combining seem to justify the additional efforts needed to realize devices based on this method. This conclusion is true, particularly in space based systems which usually require very high beam directivity and narrow spectral range of the transmitted radiation.

V. ELECTRONIC BEAM STEERING OF SEMICONDUCTOR LASERS AND LASER ARRAYS

It has long ago been recognized that the main merit of free space optical communications, namely the increased directivity of the transmitted beam, also carries the penalty of the need for highly accurate tracking, pointing and acquisition systems. Whereas typical beamwidths in the microwave regime are of the order of fractions of a degree, in the optical region of the system we have to be ready to handle beamwidths down to a fraction of an arcsecond.

Thus far the main thrust has been in developing electromechanical beam steering systems including mirrors, lenses and scanners. Although the role of those will not necessarily be eliminated in the future, there are decided advantages to implementation at least part of these functions electronically. In particular we describe an important way of achieving this goal by incorporating the steering mechanism within the semiconductor laser itself via the modification of its index of refraction. Such a monolithic configuration has the potential advantage of higher reliability and considerable savings in size and weight of the system. Another possible method is by controlling the individual phases in a phase locked array configuration (described in the previous section), in a similar fashion to microwave phased arrays.

Electronic beam steering of semiconductor lasers have already been demonstrated [27]. The operational mechanism is simple, in principle. By splitting the stripe contact of the laser to several parallel stripes, and passing different amounts of current rhough each stripe, as shown schematically in Fig. 6a, an asymmetry of the gain profile across the laser active region is established. This asymmetry influences the laser radiation mode, which have to satisfy the wave equation of the perturbed structure, and beam deflection results (Fig. 6b). Additional devices – such as position detectors for location of beacon beams – can also be incorporated on the same substrate, thus realizing on a single “chip” all the electrooptical functions of the optical transmitter unit.

A different approach for electronic beam steering is in applications where laser arrays are used in order to achieve higher levels of radiated power. These arrays can be modified by monolithically including two electrooptical modulators in tandem with each laser. These modulators may well be needed in any case in order to assure the proper operation of the array, and we can take advantage of their existence and use them for steering the beam of the array. The first modulator is incorporated within the cavity of the laser [28]. These modulators can fine-tune the oscillation frequency of the individual lasers in the array, thus alleviating the task of maintaining it phase-locked. The second modulator is external to the laser cavity, and it controls the phase of the radiation of the laser. Of course, applying a phase-shift to a single laser is of no significance to our application. However, if we have a phase-locked array of semiconductor lasers, then by individually controlling the relative phase shifts among the various lasers, we can obtain a controlled beam deflection of the entire array, in a similar fashion to microwave phased arrays. Operation of a semiconductor laser device on similar principles has been recently demonstrated [29]. We should also note that the dynamic range of the beam steering in this case is contained within the far-field pattern of the individual lasers of the array.

An example of a proposed one dimensional beam-steerable semiconductor laser array is shown in Fig. 7. The figure shows a schematic configuration of one half of a symmetric four-element array. Several technical details are omitted, but the main ingredients of the device – the laser section and the modulators – are clearly depicted. Extension of such arrays to more than four elements is straightforward. Arrays of the types described in this section may be useful in applications which call for a single and stable mode operation of semiconductor light sources in systems where the amount of power needed is beyond the capability of a single injection laser device.

VI. CONCLUSIONS

The various devices described in the preceding sections show the large potential of AlGaAs laser technology to free space optical communication systems. These solid-state components which can generate and modulate light, combine the power of several sources, and perform at least part of the beam pointing functions, clearly both advance the technological state of the art and enhance the possibility of realizing space-based optical communication systems.

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This work was supported by the National Aeronautics and Space Administration under Contract NAS7-100 at the Jet Propulsion Laboratories, Pasadena, California

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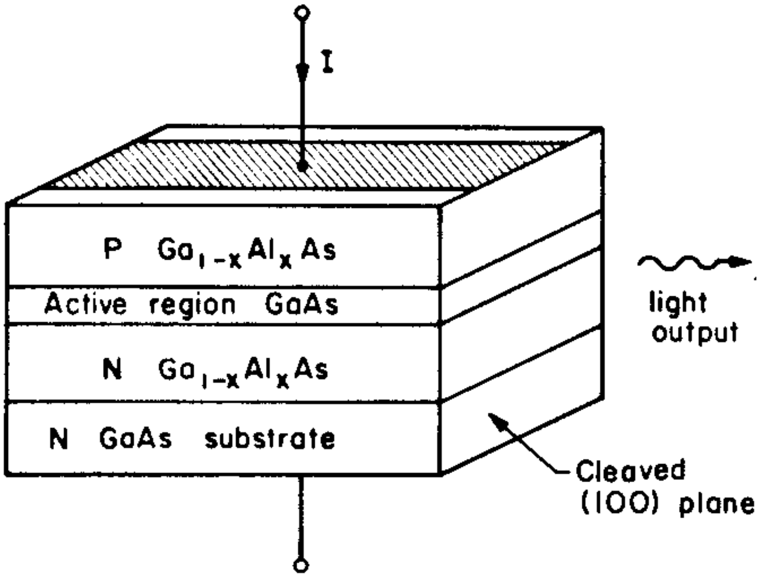
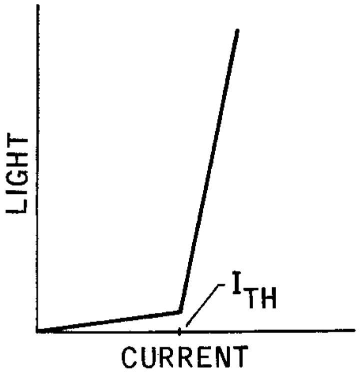


Fig. 1. Schematic drawing of an AlGaAs injection laser.



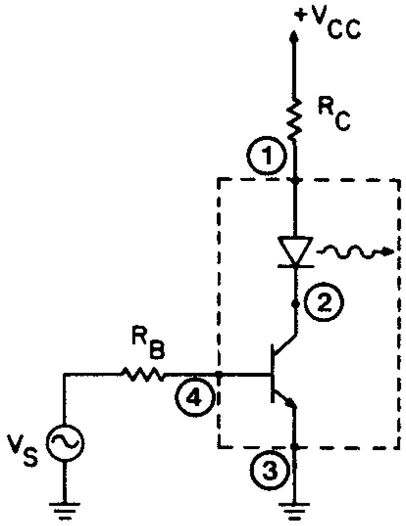


Fig. 2. Typical light vs. current characteristics of a semi-injection laser.

Fig. 3. Laser diode and its driving circuit. The dashed box contains the components integrated in the translaser.

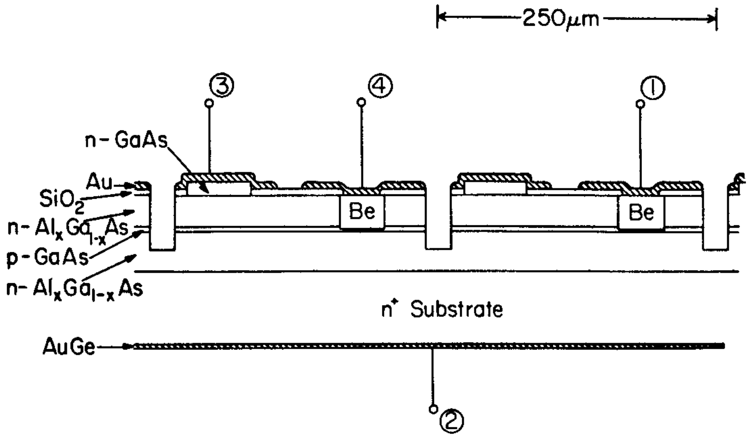


Fig. 4. Schematic cross-section of the integrated transistor-laser.

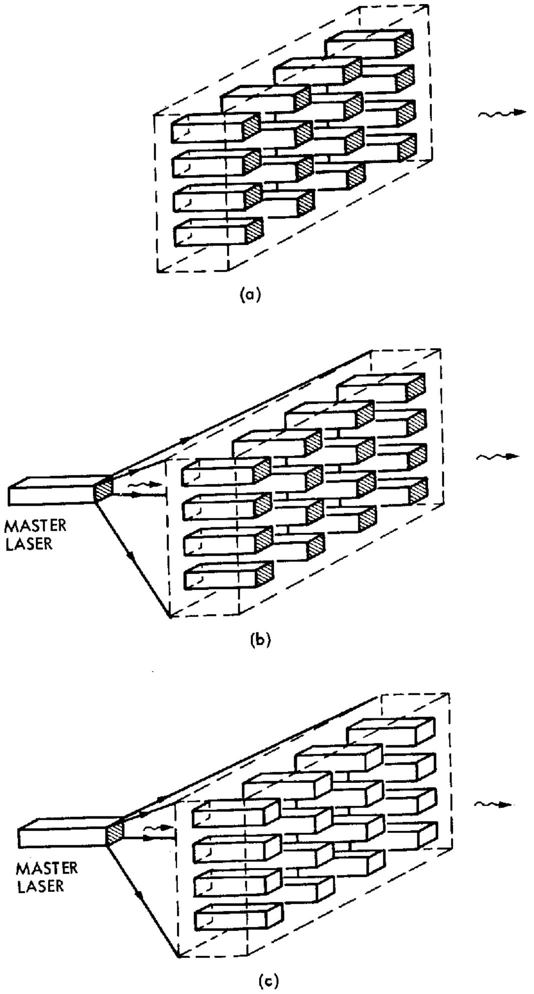


Fig. 5. Schematic configurations of coherent power combining methods.
(a) Mutual coupling,
(b) Injection locking (the array elements are lasers),
(c) Coherent amplification (the array elements are amplifiers).

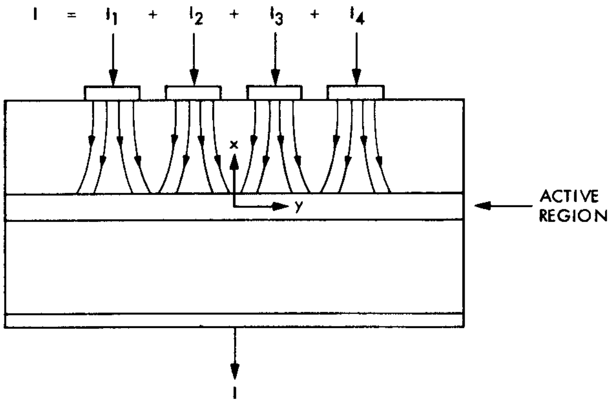


Fig. 6a. Schematic cross-section of a multiple stripe laser.

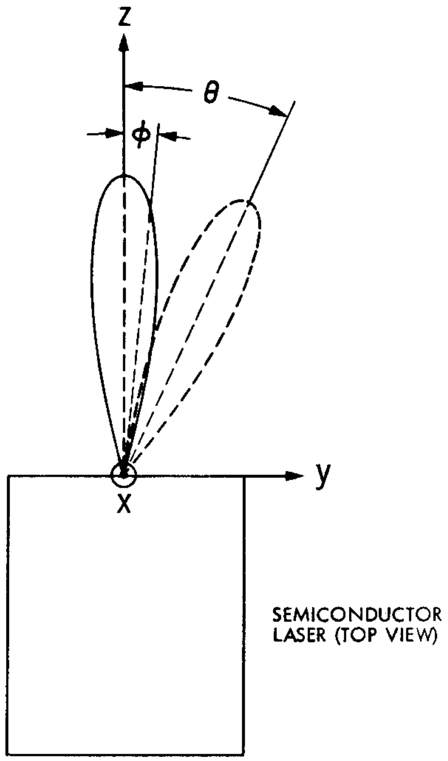


Fig. 6b. Schematic configuration of semiconductor laser beam steering.

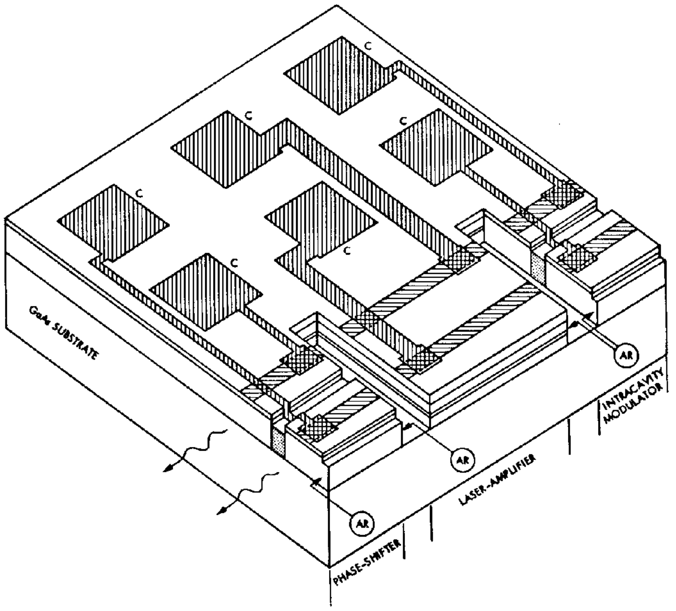


Fig. 7. Schematic layout of a one-dimensional 4-element beam steerable semiconductor laser array. (Only one-half of the symmetric array is shown).