PREFACE

Lightwave technology is breaking down barriers in communications and in computing due to advances in semiconductor integrated circuit technology. That is why the field of light wave communications faces more challenges, more excitement, more fun and a greater opportunity for society to derive maximum benefit from the almost exponentially increasing information capacity of light-wave systems. Semiconductor materials are being increasingly important for an ever-widening applications that range from radios, welders, solar batteries, optical interconnects, optical storage, CD reading – writing systems, optical telecommunications, high resolution spectroscopy and many more devices to stimulate intensive research efforts. Semiconductor lasers have been anticipated as a ‘key’ device in fiber optic communications and optical information processing due to such superior features as their small size, high efficiency and high-speed modulation characteristics. Such semiconductor materials as GaAs, InP and related compounds have bright prospects for semiconductor lasers, integrated up to electronic devices and high-speed electronic circuits.

There has been a problem on mass-productivity of light wave components, since very precise optical alignment and couplings are required. In order to overcome this problem, scientists proposed stacked planar optics. Multi-mode optical devices are being used for a variety of applications in subscriber systems and local area networks by the way of star coupler and branching circuits. To make stacked planar optics, all optical devices must have a planar structure. 2-D array of planar microlens with reasonable size and numerical aperture are effective to achieve wide variety of light wave technical fields. Microlens with distributed – index of refraction has been widely utilised for optical component in fiber communication systems. An array of microlenses on a planar substrate is required to focus and collimate the light in optical circuits.
In the research for an optical integrated circuit, the development of micro-fabrication technique is one of the essential problems. Recently, ultra-thin layer structures are of interest in the area of semiconductor optical devices. Essentially its applications to (i) quantum well semiconductor lasers (ii) multi-layer avalanche photo diodes (iii) surfaces emitting layers with multi-layer reflecting mirrors (iv) surface emitting layers with distributed feedback structure and (v) current block layer by the use of pin structure, are of great importance. For applying a distributed index planar microlens to light wave components and opto-electronic systems, a sufficient numerical aperture of a lens is required to accept light from semiconductor lasers and optical fibers. The importance of uniformity and reduction of aberration can be achieved on a large number of planar microlens arrays. A large-scale integration of light wave component would be possible on the basis of the stacked planar optics.

The thesis consists of nine chapters in all. The First Chapter gives a general introduction with brief discussions on the basic ideas of planar microlens in first section of this chapter and semiconductor laser in second section. The third section of the chapter discusses the density matrix theory to study the semiconductor laser characteristics.

The Second Chapter illustrates a detailed study of the 2-D arrayed distributed-index planar microlens towards its realisation and improvement. It is made clear that theoretically and experimentally how the 3-D index distribution in a planar microlens is formed in the fabrication process. The combination of both drift and thermal diffusion of ions plays an important role in achieving an indexed profile for low aberration. The lens dimension and migration time are determined mainly by ion drift aided by the electric field. A very strong concentration dependency exists in the diffusion coefficient and this brings about an upward convex index shape up to the periphery resulting in full utilisation of the index difference.
A distributed planar microlens was developed with the help of Tokyo Institute of Technology (TIT) which fabricated by field assisted diffusion of metal ions into a planar glass substrate through a mask (Electro-migration technique). The substrate is a planar glass of $40 \times 40 \times 3 \text{ mm}^3$ where planar microlens were formed as a $17 \times 17$ matrix with a $2 \text{ mm}$ pitch. The radius of the mask is $50 \text{ \mu m}$ and a diameter of the resultant lens $0.9 \text{ mm}$. The depth of the diffusion region is $\sim 0.45 \text{ mm}$ which is nearly equal to the radius of the resulting lens.

The 2-D arrays of branching components with a configuration of stacked planar optics are discussed in this chapter. The coupled pair of the planar microlens has been used as a collimator and focuser of the branching component. The low coupling loss in the branching component indicates the possibility of good quality 2-D arrayed components using the planar microlens since various kinds of light wave components such as an optical tap, a wavelength demultiplexer, an optical switch, a directional coupler and so on can be fabricated with the off-axial characteristics. A new development of 2-D arrayed distributed index planar microlens and a related measuring system for characterising micro optics components are also discussed in this chapter.

The Third Chapter contains a novel study on coupling property of distributed-index microlenses. An investigation of the performance of distributed-index microlenses as coupling elements has been analysed in terms of phase space representation of ray tracing method for characterising mode distribution in micro-optical devices. The trajectory of rays in each microlens of the branching circuit can be expressed in phase space derived from ray equations and the initial condition of the input rays. The coupling efficiency can be calculated as the ratio between the number of light rays leaving the focussing microlens to those entering the collimating microlens as

(iii)
depicted with the associated configurations. The value of coupling efficiency for rod and planer microlenses have been determined from the respective phase space configurations due to the lateral offset of coupling elements.

The Fourth Chapter is devoted to theoretical aspects of surface emitting room temperature injection lasers. A simple rate equations was used and analysed to reduce the normalised threshold current density factor of the surface emitting (SE) laser. It is concluded that the higher reflectivity of end mirror, shorter cavity length and thicker active layer are effective for lowering the normalised current density. Actually, the GaInAsP/InP SE laser with shorter cavity length which operates at 1.22 μm of wavelength in single longitudinal mode at 77 K has been discussed. High-normalised threshold current density is considered to be due to unexpected low reflectivity of the annealed mirror. However, further reduction of the normalised threshold current density could be achieved by increasing the active layer thickness and mirror reflectivity. To achieve easy room temperature oscillation, it would be necessary to adopt some new structure such as multilayer dielectric mirrors, quantum well structure and so on.

The Fifth Chapter deals with the spontaneous emission factor of injection lasers. A theoretical formula for the spontaneous emission factor of the injection laser is derived with the help of classical electromagnetic theory. According to the formula derived, the spontaneous emission factor is inversely proportional to the volume of the active region of the laser and the spectrum width of spontaneous emission and is proportional to the fourth power of the wavelength. The spontaneous emission factor is almost independent of the injection current. Ultimately, thresholdless lasers may be obtained. The possibility of the suppression of the relaxation oscillation by reducing the volume of the active region was suggested theoretically in this chapter.
The Sixth Chapter contains a detailed study of modulation limit of semiconductor lasers by some parametric modulation schemes. An attempt has been made to calculate the limit of modulation speed of semiconductor lasers with various modulation schemes such as (i) gain switching (ii) the modulation of non-radiative recombination lifetime of minority carriers and (iii) the cavity Q by small signal analysis and they are compared with the direct injection modulation. The maximum modulation frequency for the gain and Q modulation can exceed the resonance-like frequency $f_m$ by the factor of $b$, which is the coefficient of the time derivative of modulation parameter. But the modulation of non-radiative lifetime of carriers is not different from the direct injection modulation. A solution for the carrier lifetime modulation of LED is obtained and it is found that there exists a possibility of wide band modulation in this scheme.

The other factors, which limit the maximum modulation frequency are (i) the coherent time of the matrix element associated with the dipole transition. At such a short period of time, the rate equation representation may not make sense and we have to discuss in terms of a series of density matrix equations and (ii) CR time constant of the device. The laser noise is discussed only from the viewpoint of spontaneous emission. But it should be remembered that there might be other intensity and frequency fluctuations in the parameters with high frequency. Therefore, there is a lot of scope to extend this present work on the study of modulation capability and noises of semiconductor lasers and LED's in Ultra-high frequency region.

A theoretical aspect of single wavelength oscillation in semiconductor laser at high-speed pulse modulation is presented in the Seventh Chapter. Multi-mode behaviours of semiconductor lasers at high-speed pulse modulation are theoretically investigated by solving the multi-mode rate
equations. The gain has assumed to be homogeneous and the excitation has given by a squared-cosine pulse current.

An attempt has been made in Eighth Chapter for the first time to calculate the low-noise properties of a quantum box travelling-wave semiconductor laser amplifier using density matrix theory. The main reason for low noise characteristic in the quantum box structure is due to (i) the carrier density which is concentrated at the gain peak wavelength and (ii) total carrier number required for amplification. It was found that the sharp gain characteristic of the quantum box structure works as a narrow bandpass filter and reduces the spontaneous-spontaneous beat noise. It is also noticed that the smaller wave-guide loss and smaller population-inversion parameter of the quantum box structure reduce the signal-spontaneous beat noise and the noise figure can be reduced to \(~3.5\) dB which is close to theoretical limit of 3 dB. Hence, using multi-dimensional quantum-size such as quantum film and quantum wire semiconductor lasers can enhance the low noise characteristics.

The last Chapter deals with the theoretical analysis of electric–field-induced refractive index in InGaAsP/InP multi quantum well (MQW) structure using density matrix theory. A theoretical estimation of change in refractive index due to an electric field applied perpendicular to the MQW layer has been attempted. If an electric field is applied perpendicular to the MQW layers, the energy eigen values in the quantum well changes and the wave functions of the electrons and holes shift to the lower energy. Owing to these reasons, the dipole moment is formed by couplings of electrons and holes between the same quantisation numbers of energy levels. Using the dipole moment, energy levels, absorption coefficients and the refractive index are determined for electron and hole pairs and they are correlated by density matrix theory.
A part of the material presented in this thesis has been contributed in the form of papers in various International and National Conference / Symposium as follows:

1. 2-D arrayed Distributed-Index Planar Microlens

2. A Novel Study on Coupling Property of Distributed Index Microlenses

3. Theoretical Aspects of Surface Emitting Room Temperature Injection Laser

4. Spontaneous Emission Factor of Injection Lasers
5. Modulation Limit of Semiconductor Lasers by some Parametric Modulation Schemes

6. Theoretical Aspects of Single Wave Length Oscillation In Semiconductor Laser at High-Speed Pulse Modulation
XXVI National Symposium of the Optical Society of India on Optics and Opto-Electronics, February 4-6, 2000, REC, Warangal, A.P., Communicated to "Journal of Optics".

7. Low-Noise Characteristics of Semiconductor Laser Amplifier using Density Matrix Method
XXVI National Symposium of the Optical Society of India on Optics and Opto-Electronics, February 4-6, 2000, REC, Warangal, A.P., Communicated to "Journal of Optics".