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Review

Diode lasers: From laboratory to industry

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ABSTRACT

The invention of first laser in 1960 triggered the discovery of several new families of lasers. A rich interplay of different lasing materials resulted in a far better understanding of the phenomena particularly linked with atomic and molecular spectroscopy. Diode lasers have gone through tremendous developments on the forefront of applied physics that have shown novel ways to the researchers. Some interesting attributes of the diode lasers like cost effectiveness, miniature size, high reliability and relative simplicity of use make them good candidates for utilization in various practical applications. Diode lasers are being used by a variety of professionals and in several spectroscopic techniques covering many areas of pure and applied sciences. Diode lasers have revolutionized many fields like optical communication industry, medical science, trace gas monitoring, studies related to biology, analytical chemistry including elemental analysis, war fare studies etc. In this paper the diode laser based technologies and measurement techniques ranging from laboratory research to automated field and industry have been reviewed. The application specific developments of diode lasers and various methods of their utilization particularly during the last decade are discussed comprehensively. A detailed snapshot of the current state of the art diode laser applications is given along with a detailed discussion on the upcoming challenges.

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1. Diode lasers: An overview

An exponential growth in the use of diode lasers has been observed in almost every area of pure and applied sciences. A wide variety of the semiconductors propelled the invention of a variety of diode lasers that opened several new ways research. Most of the electronic industry giants and many research laboratories are now competing to manufacture novel ranges of semiconductor materials. The diode laser based systems are being utilized in several areas like atomic and molecular spectroscopy, interferometry, and development of frequency standards, metrology, atomic optics, and optical communication industry [1] etc. due to their remarkable properties. Owing to the compactness, low power consumption and reasonable cost; the diode lasers have been acknowledged as user friendly and universally available spectroscopic sources for both established and emerging fields. Chemical analysis and process control, atmospheric chemistry, medical applications and cancer recognition, applications to security and explosive detection, monitoring of air and water quality, vegetation, remote sensing, industrial and traffic emissions, artwork characterization, etc. are some examples [2].

The invention of tunable, narrow bandwidth diode lasers dramatically changed the scenario of laser science and proved extremely valuable in probing the atomic structures. The first diode lasers developed in 1962 by the researchers at General Electric (GE) and International Business Machines (IBM) corporations were pulsed GaAs lasers having high current densities and working at cryogenic temperatures. Due to these shortcomings the diode lasers were initially not considered as application friendly. A decade later, in 1970, a breakthrough in diode laser technology came with the successful demonstration of continuous-wave operation of diode lasers at room temperature at the Bell Laboratories, USA as well as in the Soviet Union [3]. The heart of laser diode operation is the electron–hole recombination in the active layer of laser diode chip [4]. In the active layer, a *p–n* junction is formed owing to the presence of two types of charge carries (i.e. electrons and holes). Light is generated when the electrons in the conduction band recombine with holes in the valance band. This process of recombination is the central mechanism in a laser diode (LD) as shown in Fig. 1. The wavelength of the emitted laser light depends on the energy gap between these two bands. The population inversion is achieved by supplying suitable electric current to the device while the condition of optical resonator for lasing action is established by cleaving the facets parallel to the diode junction, and thus, a *p–n* junction diode is converted into a laser diode [5]. When forward bias is applied, the heterobarrier in the double-heterostructure of LD chip confines the carriers within the active layer. The gain increases due to the carrier population inversion. The refractive index of the active layer is a little higher than those of cladding layers (layers above and below of active layer) which confine the generated light within the active layer. Therefore, laser effectively oscillates there. A light standing wave with its wavefront parallel to the cleaved facets is created due to this back and forth traveling of light within the laser cavity. Longitudinal mode expresses the standing wave condition in the direction of cavity length (*z*-direction) as shown in Fig. 2. Cavity resonance can take place at multiple wavelengths in view of the fact that cavity length is incomparably longer than the light wavelength. The particular wavelength at which the cavity gain becomes maximum, will produce a stable standing wave. However, transverse mode of light that is divided into parallel and perpendicular transverse modes lying parallel and perpendicular respectively to the active layer; define the shape of the diode laser beam.

Despite compactness and ease in use, solitary diode lasers have some intrinsic limitations like multimode nature and large linewidths owing to the short cavity lifetime along with strong coupling between amplitude and phase of the intracavity optical field that turned out potentially serious in certain applications [6]. Spatial uniformity and wavelength stability of laser beam become fluctuating under volatile ambient conditions in case of solitary diode lasers. Though it was not an issue in the case of some widespread applications like CD player lasers; but in more scientific applications the detection of atomic and molecular resonances became extremely difficult. The advancement in diode laser science and technology was required to meet these challenges. Then the sensitivity of diode lasers to external perturbations was utilized as a standard method for improving their poor

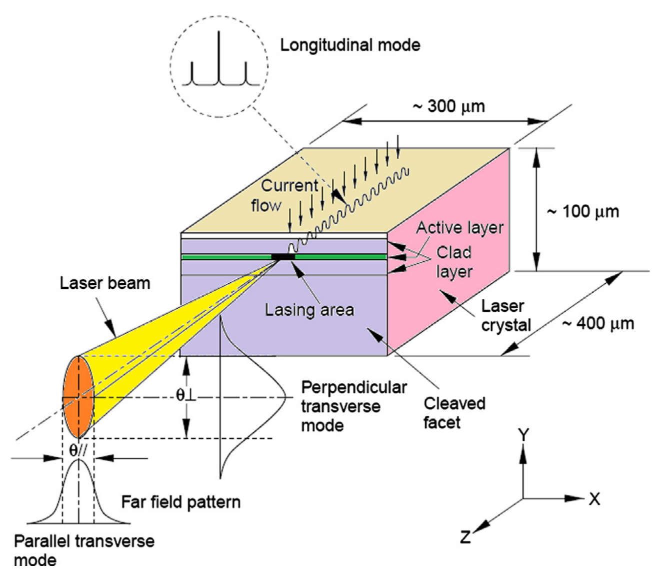

Fig. 2. Longitudinal and transverse modes of diode laser beam profile.

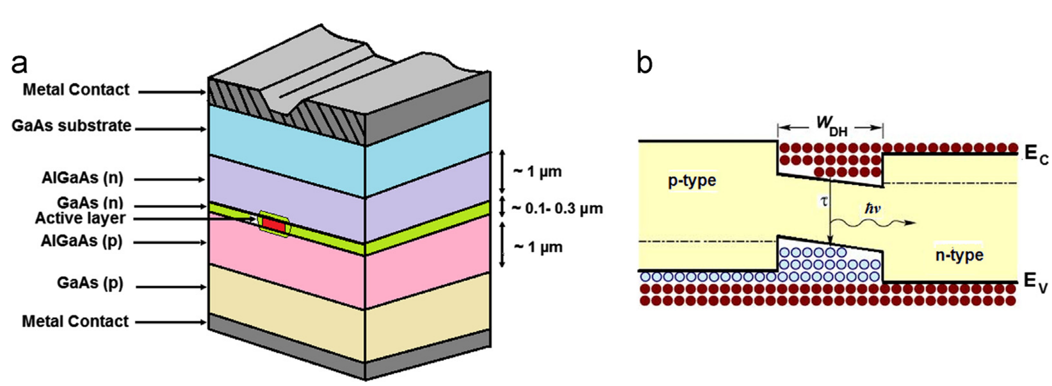

Fig. 1. (a) Laser diode chip (Double heterojunction structure) (b) Electron –hole recombination process in LD chip.