Basic Principles And Fabrication Of Distributed Feedback Lasers

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***Abstract*—This paper is a theoretical explanation of the basic working principles of lasers, a particular attention is posed to the peculiar characteristics of DFB lasers and their fabrication. (*Abstract*)**

***Keywords*—laser, single mode lasers, DFB laser, Bragg gratings, nanoimprinting** *(key words)*

I. Introduction

In many scientific and technological fields, coherent and monochromatic light sources are fundamental. In particular, the realization of easy tunable lasers with a very narrow bandwidth, is a key aspect in the modern WDM optical communication systems. In the following, the basic physical working principles of lasers will be discussed (a wide explanation can be found in [1]), then particular attention will be posed in the description of Distributed Feedback Lasers (which represent a solution to most of the critical aspects cited above) and their fabrication through the nanoimprinting technique.

II. Basic Principles Of Lasers

A. Stimulated Emission

As explained in [2], the fundamental physical principle at the basis of coherent emission and optical amplification is the stimulated emission of photons, in fact LASER means Light Amplification by Stimulated Emission of Radiation.

Considering, as in [2], an atom with two energy levels E_1 and E_2, where $E_1 < E_2$, if an electron at level E_2 interacts with an incoming photon of energy $E = h\upsilon = E_1 - E_2$, the electron decays from level E_2 to E_1 causing the emission of a photon with same: energy, frequency, polarization and phase of the incoming one (as illustrated in Fig. 1). In brief, starting from one photon, two perfect coherent photons have been obtained. The material where stimulated emission occurs, it's called active medium.

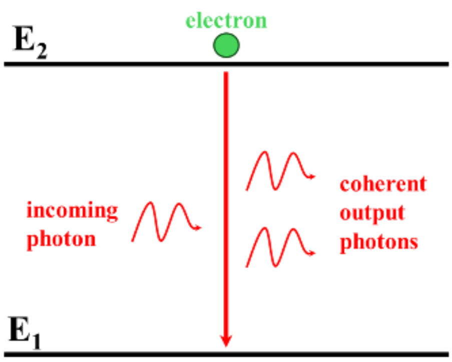

Fig 1. Stimulated emission

B. Pumping and Population Inversion

According to [2], in normal equilibrium conditions, most of the electrons would be at E_1 and few at E_2. To make possible the stimulated emission, it's essential to promote some electrons from E_1 to E_2 through a process called pumping. However, to ensure that the stimulated emission would be the dominant phenomena, it's fundamental that E_2 is more populated than E_1, this condition is called population inversion.

C. Laser Levels

With only two energy levels it's impossible to achieve population inversion, because pumping and stimulated emission are in competition, therefore, as explained in [2], a working laser needs at least three energy levels to separate the two processes, see Fig. 2. A four-level laser can provide higher efficiency because the population inversion condition can be obtained pumping a very few number of electrons as illustrated in Fig. 3.

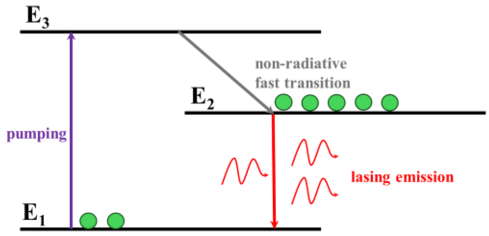

Fig 2. Three-level laser

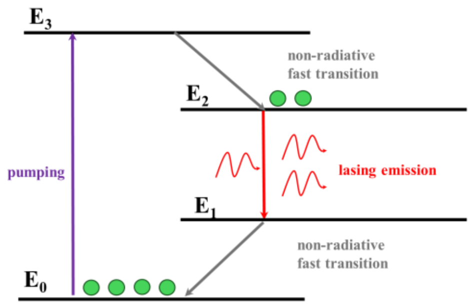

Fig 3. Four-level laser

D. *Laser Cavity and Modes*

In [2] is explained that, for a lasing emission is required a huge number of coherent photons and this is achieved by putting the active medium inside an optical resonator which provides positive feedback and filtering. One of the simplest resonators is the so-called Fabry-Perot, which consists in a cavity with two mirrors at the ends. The frequencies that can survive inside it, given by (1) and reported in [3], defines the cavity modes. In (1) n and L are respectively the refractive index and the length of the cavity while m is an integer.

$$\upsilon_m = m \cdot \frac{c}{2nL} \tag{1}$$

As explained by [3], the output spectrum is the superposition of these modes with the optical gain spectrum of the laser as qualitatively shown in Fig. 4.

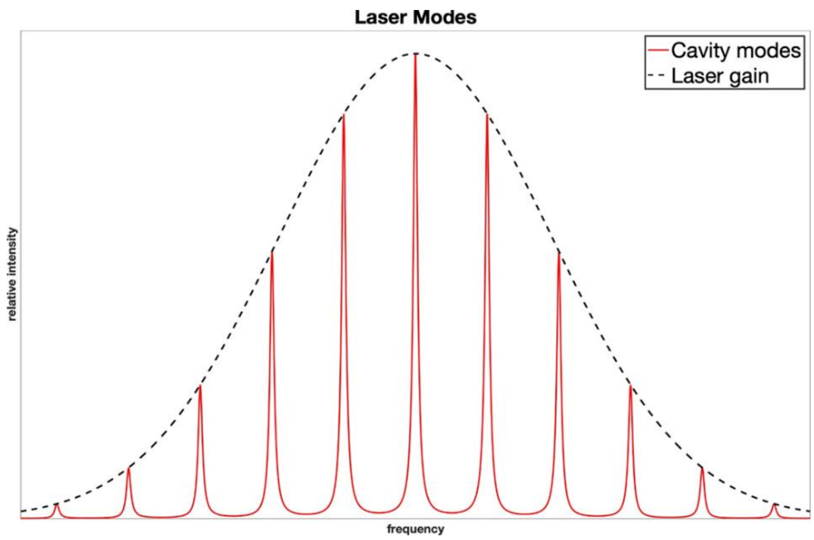

Fig 4. Qualitative output spectrum of a Fabry-Perot cavity laser

III. Characteristic Aspects of Distributed Feedback Lasers

A. *Key Aspects and Structure*

As explained by [5], in many applications is desirable to have a laser with a spectrum as narrow as possible, ideally a single frequency laser. In practice this is impossible to achieve but, with some improvements, it's possible to design a single mode laser with high modal purity. A practical implementation is the DFB laser, which is a laser diode, where the cavity is constituted by a Bragg grating.

While in a simple Fabry-Perot laser diode the discontinuity semiconductor-air provides the necessary optical feedback, as illustrated in Fig. 5 and explained in [4], in a DFB laser the feedback is distributed. As says [5], waves travelling from left to right are partially and periodically reflected by the Bragg grating and these are amplified by the active medium constituting waves that travel from right to left as illustrated in Fig. 6.

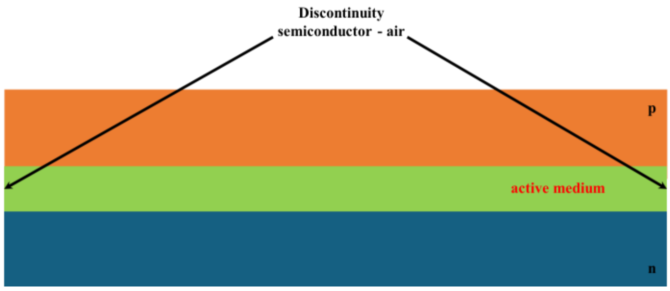

Fig 5. Approximate structure of a laser diode

Fig 6. Waves travelling in a DFB laser

B. Spectrum

These opposite travelling waves can create a standing wave only if they are coherently coupled. As reported in [5], the allowed DFB modes are given by (2) where: λ_B is the Bragg wavelength given by (3), n is the effective refractive index given by (4), d_1 and d_2 are the thickness of the n_1 and n_2 regions, Λ is the grating period, q and m are integers.

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1) \qquad (2)$$

$$q\frac{\lambda_B}{n} = 2\Lambda \qquad (3)$$

$$n = \frac{n_1 d_1 + n_2 d_2}{\Lambda} \qquad (4)$$

In theory this is not a single mode laser because there are two modes placed around λ_B. However as said in [5], in practice the corrugation length L is so much larger than Λ so that the two modes are identical. Reference [5] reports that typical telecom DFB laser diodes have a spectral width less than 0.1 nm at 1550 nm.

C. Tunabilty

Reference [5] points out one defect of DFB lasers, that is the peak wavelength dependance on temperature. This is because Λ and n change with temperature. So, a precise control of temperature is needed to avoid peak wavelength shifting.

However, as stated in [5], this undesired effect can be exploited to realize finely tunable lasers by finely controlling the temperature.

IV. DFB Laser Fabrication Through Nanoimprinting

A. Advantages of Soft UV Nanoimprint Lithography

As reported in [6], nanoimprint lithography (NIL) is a next-generation technology for patterning narrow linewidths on a substrate at low cost and high throughput. Its resolution is not constrained by the wavelength of light, and a single template can be employed to precisely reproduce the same pattern across multiple wafers. Moreover, soft, flexible NIL stamps offer several advantages compared to the rigid ones, for example, they can adapt to the substrate surface, allowing uniform imprinting over an entire wafer, also in presence of dust particles, with an extremely high resolution (≈ 2 nm), in a single imprint step.

B. Practical Aspects of UV-NIL

Reference [6] says that, for GaAs and InP substrates (whose diameter for optoelectronics applications is typically 2” or 3”), if a flexible stamp is used, it can be detached from the wafer with very low mechanical force, reducing the risk of defects or damage and the whole wafer can be patterned with a single imprint step.

In [6] is shown how the effective hardness of the stamp and the viscosity of the resist can affect the thickness of the imprinted layer, in particular, an effectively harder stamp can take advantage of the reduced viscosity of the resist, as the stamp is less prone to deformation. So [6] tried to increase the effective hardness of the stamp.

Again [6], highlights the economic reasons favoring the use of soft stamps in diode laser fabrication, such as that, the throughput of full-wafer NIL is 10–20 wafers an hour. In [6] is stated that, this type of stamp will play a key role in the imprinting of surface reliefs on 2” and 3” wafers, in particular, if simultaneous micro- and nano-patterning is required.

In conclusion, [6] believes that soft UV-NIL is a promising nano-patterning approach, which is suitable for accurate pattern generation on fragile full-wafer GaAs and InP substrates.

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