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Self-mixing interference in distributed feedback laser diode with multiple external cavities

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Abstract

The self-mixing interference in distributed feedback laser diode (DFB-LD) with multiple external cavities is analyzed. Each external cavity is considered to be an optical thin film, and the equivalent reflectivity can be got from the theory of the thin film optics, the general expressions of gain and frequency in compound laser cavity are theoretically deduced. This principle is helpful to build the fiber-coupled self-mixing interference system. Considering that different parameters have influence on self-mixing interference, we make some simulation analysis at different conditions. The output of self-mixing interference is analyzed in numerical analysis, and the amplitude variations of the output gain is discussed along with different parameters, e.g., the coupling coefficient, the linewidth enhancement factor, and the reflection coefficient of external reflector.

Keywords: Self-mixing; Distributed feedback; Multiple external cavities

1. Introduction

A portion of light emitted from a laser source is reflected or scattered by an external object, and then backs into the resonant cavity of laser. The feedback light taking information of the external object then mixes with the light inside the cavity, and modulates the output signal of laser power. The feedback light is coherent with the light inside the laser's cavity, and this forms self-mixing interference in lasers.

The self-mixing interference comes from the external optical feedback effect of lasers. People tried to eliminate the influence of the optical feedback previously, but utilized the optical feedback to achieve the velocity [1–3], distance [4] and displacement [5] measurement actively later. Recently, new phenomena and experimental results using self-mixing effect have emerged continually. Fiber is applied in self-mixing interference system extensively because of its instinct characteristic. For instance, Koelink et al. used fiber-coupled technique in self-mixing interference Doppler velocimeter in 1994 [6]. Hauptmann et al. used fiber-coupled technique in self-mixing interference silicon resonator sensor system in 1996 [7]. Up to now, the theoretical analysis concerning fiber-coupled self-mixing interference system has not been perfected. In practical application, we should take account of the influence from two facets of the fiber out of the laser cavity, which is the self-mixing interference with multiple external cavities.

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Our group analyzed self-mixing interference effect of $\lambda/4$ phase-shifted index-coupled [8] and gain-coupled (GC) [9] distributed feedback (DFB) lasers with single external cavity in last 2 years. In this paper, we focus on the self-mixing interference effect of distributed feedback laser diode (DFB-LD) with multiple external cavities. The expressions of frequency variation and gain are deduced, and the equivalent reflectivity of the whole external cavity is analyzed. We take GC DFB-LD for example in numerical analysis. The influence of different parameters on the self-mixing interference is analyzed, including the amplitude variations of the output gain.

2. Theoretical analysis

2.1. The self-mixing interference of DFB-LD

Fig. 1 represents the self-mixing interference system of DFB-LD with single external cavity. r_l, r_r are, respectively, the reflectivities of two laser facets, L is the laser cavity length, there is an external target with the reflectivity r, and the external cavity length is L_{ext}.

Under the condition of weak feedback level, provided a reflector with the reflectivity r on the right-hand side, the equivalent reflectivity of the right-hand facet can be written as

$$r'_r = r_r + (1 - r_r^2) r \exp(-j\omega\tau), \tag{1}$$

where ω is the emission frequency, $\tau = 2L_{ext}/c$ is the external round-trip time, and c is the velocity of light in vacuum. The complex feedback sensitivity defined in Ref. [10] is $C_r = \Delta qL/[r \exp(-j\omega\tau)]$, C_r is a complex feedback sensitivity, which depends only on the proper laser parameters in the limit of a weak feedback level.

We can obtain the emission frequency and gain variations as follows, here α_m is the linewidth enhancement factor:

$$\Delta\omega\tau = \frac{2}{n}(1+\alpha_m^2)^{1/2}|C_r||r|\frac{L_{ext}}{L}\sin[\omega\tau - \arg(C_r) - \arg(r) - a\tan(\alpha_m)],$$
$$\Delta G = \frac{4}{n\pi}|C_r||r|\frac{L_{ext}}{L}\cos[\omega\tau - \arg(C_r) - \arg(r)]. \tag{2}$$

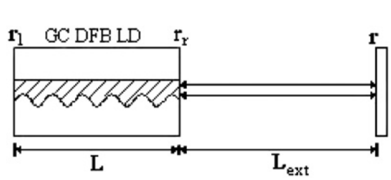

Fig. 1. The self-mixing interference system of DFB-LD.

2.2. The self-mixing interference of DFB-LD with multiple external cavities

According to the thin film optics theory, the optical beam reflected by two facets of the film form thin film interference. Extending this theory, the self-mixing interference system of multiple external cavities can be predigested.

Fig. 2 represents the self-mixing system with multiple external cavities. r_l, r_r are the reflectivity of the left and right laser facets, respectively, L is the laser cavity length, there are $n-2$ reflectors forming multiple external cavities located on $z = L + L_3,\ L + L_4, \ldots, L + L_{n-1},\ L + L_n$, the reflectivities are $r_3, r_4, \ldots, r_{n-1}, r_n$, respectively. Two adjoining reflectors formed a thin film optics system. We adopt iterative algorithm from the last two reflectors:

$$r'_{n-1} = r_{n-1} + \eta_{n-1}(1 - r_{n-1}^2) r_n \exp(-j\theta_n), \tag{3}$$

$$r'_{n-2} = r_{n-2} + \eta_{n-2}(1 - r_{n-2}^2) r_{n-1} \exp(-j\theta_{n-1}) + \eta_{n-1}\eta_{n-2}(1 - r_{n-2}^2)(1 - r_{n-1}^2) r_n \times \exp[-j(\theta_{n-2} + \theta_{n-1})]. \tag{4}$$

The equivalent reflectivity of whole external cavity was deduced as:

$$r'_r = r_r + \eta_r(1 - r_r^2) r_3 \exp(-j\theta_3) + \eta_r\eta_3(1 - r_r^2)(1 - r_3^2) r_4 \exp[-j(\theta_3 + \theta_4)] + \cdots + \eta_r\eta_3\ldots\eta_{n-1}(1 - r_r^2)(1 - r_3^2)\ldots(1 - r_{n-1}^2) \times r_n \exp[-j(\theta_3 + \theta_4 + \cdots + \theta_n)]. \tag{5}$$

Here, θ_i is the phase delay between two adjoining reflectors (r_i and r_{i-1}), η_i is the coupling coefficient of plane r_i.

Let $\tau_3 = \theta_3/\omega = 2L_3/c$, $\tau_4 = (\theta_3 + \theta_4)/\omega = 2L_4/c, \ldots$, $\tau_n = (\theta_3 + \theta_4 + \cdots + \theta_n)/\omega = 2L_n/c$; $\xi_3 = \eta_r r_3$, $\xi_4 = \eta_r\eta_3(1 - r_3^2) r_4, \ldots$, $\xi_n = \eta_r\eta_3\ldots\eta_{n-1}(1 - r_3^2)(1 - r_4^2)\ldots(1 - r_{n-1}^2) r_n$, and Eq. (8) can be predigested as

$$r'_r = r_r + (1 - r_r^2)\{\xi_3 \exp(-j\omega\tau_3) + \xi_4 \exp[-j\omega\tau_4] + \cdots + \xi_n \exp[-j\omega\tau_n]\}. \tag{6}$$

Let $r'_r = r_r + (1 + r_r^2) r \exp(-j\omega\tau)$, under the condition of weak feedback level, the coefficient $\xi_i \ll 1$

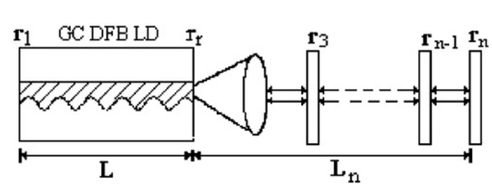

Fig. 2. The self-mixing interference system with multiple external cavities.