A Phase-Modulated Feedback Method for Testing Optical Isolators Assembled into the Laser Diode Package

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***Abstract*—We present an easy-to-implement method for measuring the isolation factor of an optical isolator mounted in front of its laser diode chip. The method is based on phase-modulated feedback that is induced by a moveable mirror reflecting the emitted power back into the laser, and it consists of measuring the intensity modulation of power that is found to be well correlated to the round-trip attenuation. Measurement sensitivities up to −80 dB in terms of isolation have been obtained. The method has been tested successfully for several kinds of laser diodes, either FP or DFB with emission in first and third windows.**

I. Introduction

It is standard practice to measure the isolation factor of an isolator much in the same way as it is for a standard insertion loss of a generic passive component (as specified, e.g., in [1]). Until now, to our knowledge, no one has attempted to measure the isolator performance *in-situ,* i.e., when it is mounted with the laser in a package.

In this letter, we propose a method for such a measurement, using the same laser diode for which the isolator is intended as a source and optical feedback of the sensing mechanism.

A key feature of the optical-feedback approach is that the generated modulation is proportional to the fraction of the field returned into the cavity and that it can be detected with very high sensitivity since the interaction process is coherent.

In addition, our approach is the only one capable of characterizing the performance of those isolators lacking the first polarizer, where suppression of the backward wave is left to the laser polarization-selectivity.

In order to discuss the principle of operation, let us refer to the experimental setup in Fig. 1, in which the output from a monomode (Fabry-Perot or DFB) laser is collimated by a Grin lens, then passes through the device under test suffering a total (two-way) power attenuation A, is reflected by a mirror at a distance L, and is focused back into the laser cavity.

Following the standard treatment of optical feedback, either as outlined in [2] or directly from the Lang and Kobayashi equations [3]–[5], it can be found that for weak retroreflection ($A \ll 1$), the laser power P undergoes an amplitude modulation around the unperturbed value P_0 proportional to the fraction $\sqrt{A}$ of the field returned into the cavity and sensitive to its in-phase field component.

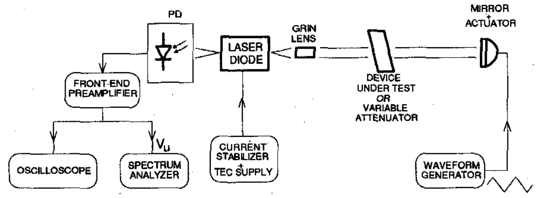

Fig. 1. Setup for the measurement of isolation with phase-modulated feedback.

This modulation can be detected by a photodetector placed at any point of the beam or, conveniently as in Fig. 1, on the rear mirror of the laser. The resulting current can be written as

$$I = \sigma P = \sigma P_0[1 + \kappa\sqrt{A}\cos 2kL], \tag{1}$$

where σ is the photodiode spectral sensitivity (A/W), $k = 2\pi/\lambda$ is the wavenumber, and $\kappa = (c/2l)/[G(N-N_0) - 1/\tau_p]$ is a dimensionless factor [3] not far away from unity for $A \ll 1$, L is the mirror distance from the laser, and the other symbols have the usual meaning [3], [5].

If we let L undergo a linear sweep $\mathrm{swp}(t/t_0)$ of amplitude ΔL on a time period t_0, i.e.,

$$L = L_0 + \Delta L\,\mathrm{swp}(t/t_0),$$

we have that the photodetected signal, during the sweep time $t = 0 - t_0$, is

$$\begin{aligned} I &= I_0 + \sigma P_0\kappa\sqrt{A}\cos[2k\Delta L(t/t_0) + \phi_0] \\ &= I_0 + I_m\cos[2k\Delta L(t/t_0) + \phi_0], \end{aligned} \tag{2}$$

where $\phi_0 = 2kL_0$ is an unessential added phase, and $I_0 = \sigma P_0$ is the dc component.

From (2), it can be seen that the detected signal I is amplitude modulated at a frequency $f_m = 2\Delta L/t_0\lambda$, which can be set in a convenient range by properly adjusting ΔL and t_0; we may also note that the amplitude of the modulated signal I_m is proportional to the square root of the (power) attenuation A, i.e., the diagram of I_m versus A has a slope of 10 dB/decade for $A \ll 1$, the same as for a coherent detection.

At increasing feedback levels, the slope first becomes less than 10 dB/decade because of external-cavity mode oscillation [2], and a value of A is then reached at which the modulation does not increase anymore due to gain saturation [6].

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TABLE I

Laser diode	Wavelength	Threshold current	Output power	Saturation attenuation	Maximum attenuation
SDL 5401	805nm	22mA	30mW@50mA	15dB	85dB
ML 2701	854nm	18mA	6mW@40mA	40dB	90dB
DFB CSELT	1530nm	26mA	3mW@40mA	25dB	75dB

The previous results suggest the following procedure to measure a generic insertion loss of a passive component with the setup of Fig. 1; the calibration curve of I_m versus A for a specific laser diode is first obtained, simply by inserting neutral density filters of known attenuation in place of the device under test and measuring the corresponding amplitude I_m at the fundamental frequency $f_m = 2\Delta L/t_0\lambda$; then the component (or isolator) is inserted, and the measured I_m value readily gives the (round-trip) attenuation A. For an isolator A is specifically the sum of isolation factor and insertion loss. The insertion loss can be subtracted from the resulting A because it is easily measured in the same setup, e.g., by putting the photodiode in place of (or before) the mirror with and without the isolator.

II. EXPERIMENT

To test the method, we used several semiconductor lasers in the setup of Fig. 1; their relevant parameters are listed in Table I. All the laser diodes were operated at the nominal emitted power through a current stabilized source and a thermoelectric controller.

The collimating lenses in the setup were Grin type, 0.23 pitch, antireflection coated at the wavelengths of emission. The residual reflection from the front surface, placed at 100 μm from the output laser facet had however no influence on modulation since it only affected the dc term in (2). The same argument applies to reflections originated at the optical surfaces internal to an isolator under test; these reflections (which properly constitute the return-loss) are excluded from the isolation-loss measurement because they give dc terms of the type $\sqrt{A'} \cos 2kL'$ in (1) and (2), which only modify the dc current I_0 and leave the modulated signal unchanged, provided they are reasonably small (i.e., A' much less than the saturation level).

As attenuators, we used single or stacked Kodak Wratten filters, mounted slightly tilted, calibrated at the wavelengths of interest by a separate measurement with an optical spectrum analyzer (±0.5 dB accuracy) [7].

The photodiodes, located on the rear facet of the lasers, were silicon pin for first window lasers, and ternary photodiodes for the third window, all backed by a front-end transimpedance amplifier with a 1 MΩ feedback-resistance.

The external cavity mirror, an Al-coated flat placed at 10–20 cm from the laser, was glued on a loudspeaker and mounted on a three-axis micropositioner for alignment. The loudspeaker was driven by a triangular waveform of low frequency ($1/t_0 =$ 1–2 Hz) in order to obtain a linear response free from ringing, and the amplitude was $\Delta L \approx 1$ mm, which corresponds to a frequency f of the sinewave function (see (2)) of about 1 kHz. Since ΔL was not adjusted to an integer multiple of $\lambda/2$, a phase discontinuity was generated at the slope changes of the triangular waveform, however, the effect on spectrum of I_m was negligible because of the many (thousands) periods of $f = 2\Delta L/t_0\lambda$ contained in t_0.

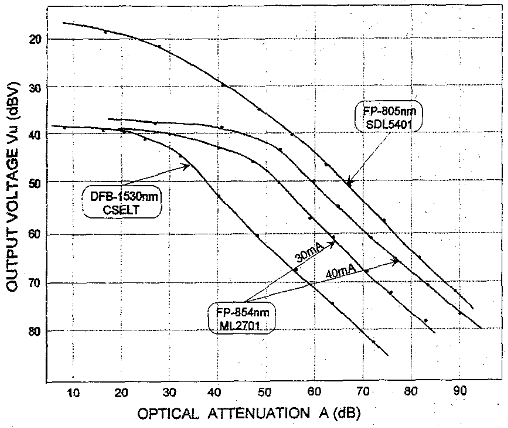

Fig. 2. Signal voltage amplitude V_u at frequency f_m, measured on the spectrum analyzer, plotted for the three laser diodes versus the (round trip) optical attenuation of the external cavity.

The photodetector output was monitored on a oscilloscope to maximize the signal during the alignment procedure, and the measurements of modulation amplitudes I_m at frequency f_m were performed by an electrical spectrum analyzer (HP35665A). No criticality of alignment was found on the full range of measured attenuations.

The calibration curves obtained for the three lasers of Table I are reported in Fig. 2. As expected, the trend is consistent with theoretical behavior (10 dB/decade) up to saturation levels of about −30 dB. Some deviations from the 10 dB/decade slope are also apparent, which have been recognized to correspond to the two- or three-mode oscillation regime due to the external cavity. It can be noticed that the achieved sensitivity is in excess of 80 dB for the (total, i.e., two-pass) attenuation. Repeatability of the curves, measured in different days, was found to be better than ±1 dB. No degradation of the lasers was evident, even when working for several hours at large feedback levels (e.g., 10–20 dB attenuation).

A comparison with standard isolation measurements was performed with the 1530 DFB Cselt laser, using a free-space, single-stage isolator made by a standard YIG crystal and two calcite polarizers [8]. Compared to the 45 (±0.5) dB isolation obtained with a standard measurement [1], our method yielded 46 (±1) dB and 1 dB of insertion loss. The setup allowed also to measure the isolation of the isolator when the first polarizer was removed, i.e., when the laser itself acted as the polarizer; in this case, the attenuation was 30 dB (more detailed data will follow in a separate paper [9]). In both cases, the orientation of the laser polarization respect to the isolator input was adjusted by a coarse rotation maximizing the through power, followed by a fine rotation minimizing the (backreflected) modulated signal read on the spectrum analyzer.

It may be worthwhile to note that the method will work equally well with polarization-insensitive isolators, even when they transversally displace the backreflected beam. Indeed, it is the scalar-product coefficient of the backreflected field projected on the laser-mode field-distribution to give the term

$\sqrt{A}$ in (1), i.e., the methods yields as the resulting isolation exactly the one of the backreflection to which the laser is sensitive.

III. DISCUSSION

To assess the ultimate sensitivity of the proposed method, let us consider the signal I_m and noise i_{nm} at the output of the detection photodiode. The noise is contributed by the sum of the following quadratic terms: a) shot noise $2eI_0BF$ of the detected (dc) current, where F is the excess noise factor due to the RIN of the laser; b) noise of the transimpedence front-end, $4kTB/R$ (limit of the feedback resistance); c) instrumental noise $v_{\mathrm{sa}}^2 B/R$ of the spectrum analyzer floor (-110 dBV). In our setup, the first term was dominant, and therefore, the S/N ratio of the detected current, taking into account that $I_m = I_0\kappa\sqrt{A}$ from (2), is

$$(S/N)_I^2 = (I_m/i_{nm})^2 = I_m^2/2eI_0BF = I_0\kappa^2A/2eBF. \quad (3)$$

Since $A \propto 1/I_m$, the S/N ratio of the current coincides with the S/N of attenuation. Letting $S/N = 1$ in (3) as a marginal working condition, we obtain as a limit of measurable attenuation $A_{\max}$

$$A_{\max} = 2eBF/(I_0\kappa^2). \quad (4)$$

With the appropriate values ($B = 100$ Hz, $I_0 = 100$ μA, and $\kappa = 0.03$, $F = 5$ (estimated)), we get from (4) $A_{\max} = 0.15 \times 10^{-8}$, a value consistent with experimental results; however, by reducing the bandwidth and increasing I_0 (which was taken at the rear mirror and was not optimized) the limit could well be increased by one or two decades before the other two noise contributions become important.

Furthermore, another comment is about the mirror actuator, which can be eliminated for by adding a current triangular waveform of proper amplitude onto the bias current of the laser, so as to modulate the laser wavelength, as discussed in [6]. The resulting signal is of the type $I_m = I_0\kappa\sqrt{A}\cos 2[k_0 + \Delta k \cdot \mathrm{swt}(t/t_0)]L$, i.e., it is equivalent to the one previously considered if the direct-amplitude modulated term $\mathrm{swt}(t/t_0)$ is subtracted from I_m. While this scheme has been found suitable for FP lasers, it is less applicable to DFB lasers because of the smaller wavelength dependence on the current.

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