Amplified-spontaneous-emission feedback circuit scheme for optical measurement with improved optical power resolutions

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Abstract: We proposed a novel optical power measurement scheme, which significantly improved optical power resolution (OPR) by implementing an amplified-spontaneous-emission feedback circuit (ASEFC) ahead of a conventional optical power meter. The scheme was named “ASEFC scheme.” The ASEFC operates in regions near the lasing threshold. The OPR characteristics of the ASEFC scheme were clarified experimentally. We demonstrated significantly improved OPRs in optical loss measurement of an optical component. The OPRs were less than 0.00014 dB, and the sensitivity was greater than 67, at a display resolution of 0.01 dB for the power meter.

Keywords: optical power measurement, resolution, amplified spontaneous emission, feedback

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Optical power resolution (OPR) is one of the most important parameters of optical power measurement in an optical power meter (PM), for application in optical communication and measurement systems [1, 2, 3, 4]. The PM typically consists of a photodetector, such as a photodiode, followed by an electric circuit. The OPR of the PM is conventionally expressed in dB (or %), and is generally an order of 0.01 dB (or 0.23%) [3, 4, 5, 6]. For example, an OPR of 0.01 dB was reported as a specification [5]. Another example stated that the OPR is limited by the polarization dependence, or interference noise phenomena of the PM, and has values of ±0.005 to ±0.015 dB for each phenomenon [6]. We proposed a novel optical power measurement scheme, which significantly improved OPR by implementing an amplified-spontaneous-emission feedback circuit (ASEFC) ahead of a conventional PM [7, 8, 9, 10]. We named this scheme “ASEFC scheme.” The ASEFC operates in regions near the lasing threshold [9]. In this study, we demonstrated an optical loss measurement in a variable optical attenuator (VOA), with significant improvements in OPR, of up to 67 times or more. For a PM with a display resolution of 0.01 dB, the resultant OPRs using the ASEFC scheme were as low as ~0.00014 dB (0.01/70 dB) or lesser.

2 Experimental setup

Fig. 1(a) shows the system configuration of the ASEFC scheme. We used a photodiode module (PDM), which comprised a photodiode followed by an electric circuit. PDM is used in many applications of optical communication/sensing systems. We set the ASEFC in front of the PDM. The cascading ASEFC and PDM made up the novel optical power meter based on the ASEFC scheme, which was named “ASEFC-PM” in this study. The optical power of the signal emitted from a light source (LS) was measured using the ASEFC-PM. We placed an optical device, namely the device under test (DUT), between the LS and ASEFC. We can measure the loss and gain of the DUT, in the cases where the DUT is a passive optical
component, and an optical amplifier, respectively. The wavelength of the light output from the ASEFC ($\lambda_{\text{out}}$) differs from that of the input light ($\lambda_{\text{in}}$). The powers of the input and output lights for the ASEFC were labeled as $P_{\text{in}}$ and $P_{\text{out}}$, respectively, in dBm units. Upon removing the ASEFC from the ASEFC-PM, the PM consists only of the PDM, and becomes a conventional PM. The optical power measurement scheme using the conventional PM was named as “conventional scheme.”

![Fig. 1. (a) System configuration and (b) experimental setup of the ASEFC scheme.](image)

Fig. 1(b) shows the experimental setup, which consisted of an LS, a DUT, an ASEFC, and a PM placed after the ASEFC (PM_{out}). A VOA was set after the LS to change $P_{\text{in}}$ and was denoted as VOA_{LS}. $P_{\text{out}}$ was measured using PM_{out}, whereas $P_{\text{in}}$ was monitored using PM_{in} through a branch located after VOA_{LS}. Each sensor head of PM_{in} and PM_{out} was Ando Electric AQ2735, and had a polarization dependent loss of 0.02 dB peak-to-peak or lesser. The frequency bandwidth of the sensor head and the averaging number for each measurement datum were set to about 20 Hz and 50 times, respectively, in order to reduce the noise in the measurement. The LS comprised a Fabry-Perot type InGaAsP laser diode (LD), with a drive current of 350 mA which was kept constant to maintain the output power and LD spectrum constant during the measurement. We carefully employed a long enough warm-up time of about two hours for the measurement system. The monitored variation in $P_{\text{in}}$ with time was less than within about 0.001 and 0.005 dB peak-to-peak in the durations of about 5 and 60 minutes, respectively, whereas the minimum display resolution was 0.001 dB. The display resolutions of the current and temperature of the driver for the LD were 1 mA and 0.01 °C, respectively. The time variations of the current and temperature in actual were estimated far smaller than the display resolutions.

The ASEFC contained a 15.9 m long spool of erbium-doped fiber (EDF) as its gain medium, and a fiber-ring feedback loop. The absorption peak of the EDF
around 1530 nm was approximately 4.7 dB/km. In the feedback loop, the ASEFC consisted of two optical isolators (ISOs) on both sides of the EDF, a wavelength-selective coupler (WSC) ahead of the EDF, an optical bandpass filter (OBPF), a branch for the output power (BRout), and an attenuator (ATT). The ATT was used for lasing threshold adjustment, in other words, input power range adjustment for the ASEFC. The average gain of the flat-gain spectrum condition of the EDF was approximately 21 dB in the C band, and the loop loss of the feedback loop was approximately 15 dB. The center wavelength and bandwidth of the OBPF were 1558 nm and 1 nm, respectively. The gain of the EDF at 1558 nm increased with P_in, and was close to 15 dB over the lasing threshold. \( \lambda_{\text{in}} \) is generally a pump or signal wavelength of the gain medium [8, 10]. \( \lambda_{\text{in}} \) was selected to be a pump wavelength (1470 nm) of the EDF in this experiment.

The optical powers, in dBm units, at points A, B, and C in Fig. 2(b) were denoted as \( P_{\text{inDUT}} \), \( P_{\text{in}} \), and \( P_{\text{out}} \), respectively. The DUT, a product of Optoquest Co., Ltd. (Model VOAA), was a VOA (VOADUT) which consisted of a micrometer, and an optical interference part. The loss of the DUT (\( L_{\text{DUT}} \)), in dB units, is given by the following relation:

\[
L_{\text{DUT}} = P_{\text{inDUT}} - P_{\text{in}}. \tag{1}
\]

The variation in \( L_{\text{DUT}} \) was denoted as \( \Delta L_{\text{DUT}} \), at constant \( P_{\text{inDUT}} \). Subsequently, we obtained the following relation:

\[
\Delta L_{\text{DUT}} = -\Delta P_{\text{in}}, \tag{2}
\]

where \( \Delta P_{\text{in}} \) was the difference in \( P_{\text{in}} \) caused by the loss variation of the DUT. Therefore, we could derive \( \Delta L_{\text{DUT}} \) using Eq. (2), applying the measured values of \( \Delta P_{\text{in}} \). In the case of the conventional case, the ASEFC in Fig. 1(a) was removed so that the output power of VOADUT was directly measured by PMout.

### 3 Experimental results

Fig. 2(a) shows \( P_{\text{in}} \) as a function of \( P_{\text{out}} \), while \( \Delta L_{\text{DUT}} \) remained constant (cf. Fig. 1(b)). The experimentally measured data, and a curve derived by numerical calculation are shown in the figure. Due to the change in \( P_{\text{in}} \) by approximately 0.16 dB, from 15.729 to 15.887 dBm, \( P_{\text{out}} \) varied by approximately 10.7 dB, from –28.212 to –17.502 dBm. Here, we introduced a parameter called “slope” or “sensitivity,” which was a differential of \( P_{\text{out}} \) by \( P_{\text{in}} \), denoted by \( S \equiv dP_{\text{out}}/dP_{\text{in}} \). The sensitivity “S” coincided with an improvement factor in the OPR owing to the use of the ASEFC scheme, if the excess noise generated in the ASEFC was negligible.

For the sake of simplicity, \( x = P_{\text{out}} \) and \( y = P_{\text{in}} \) were denoted to simplify the expressions of the equations shown below. From Fig. 2(a), \( y \) is a function of \( x \), that is, \( y = f(x) \), and \( x \) is a function of \( y \), that is, \( x = g(y) \). Hence, \( g \) is an inverse function of \( f \). To express the experimental plot of data in Fig. 2(a), we assumed the following simple tangential function:

\[
y = b \cdot \tan \left( \frac{x - d}{ab} \right) + c, \tag{3}
\]

where \( a, b, c, \) and \( d \) are constants. Then, \( x \) and \( S (= dP_{\text{out}}/dP_{\text{in}} = dx/dy) \) were given by
respectively. The calculated values of the relations given by Eqs. (3) and (5) are shown in Fig. 2(a) and (b), respectively. The best fit between the experimental and calculated values in the region of $P_{out}$, from $-26.5$ to $-19.0$ dBm approximately, where $S$ was greater than 60, was obtained using the values of the constants $a$, $b$, $c$, and $d$ as 106, 0.047, 15.807, and $-22.7$, respectively.

Fig. 2. (a) The input power and (b) the sensitivity as a function of the output power. Measured (exp.) and calculated (calc.) data are shown.

Fig. 3. (a) Measured losses of the VOADUT as a function of the micrometer position in the cases of the conventional scheme ((a) and (b)), and of the ASEFC scheme ((c) and (f)). The absolute values of the difference in optical power in the case of the ASEFC scheme are shown in (c) and (d). The regions of the micrometer position for the plots are 0-1.4 mm for (a), (c), and (e), and 0-1.0 mm for (b), (d), and (f).
In the case of the conventional scheme, we directly measured the output power from \( \text{VOA}_{\text{DUT}} \) \( (P_{\text{outDUT}}) \), using \( \text{PM}_{\text{out}} \), as a function of the position of the micrometer of \( \text{VOA}_{\text{DUT}} \) \( (z) \). \( P_{\text{outDUT}} \) at \( z \) was denoted as \( P_{\text{outDUT}}(z) \). The display resolution of the digital power meter \( \text{PM}_{\text{out}} \) \( (R_{\text{PM}}) \) was set to 0.001 dB, which was its minimum display resolution. The loss of \( \text{VOA}_{\text{DUT}} \), that is, \( \Delta L_{\text{DUT}} \), was given by the relation

\[
\Delta L_{\text{DUT}}(z) = P_{\text{outDUT}}(z = 0) - P_{\text{outDUT}}(z)
\]

at constant \( P_{\text{inDUT}} \). Fig. 3(a) and (b) show \( \Delta L_{\text{DUT}}(z) \) in milli-decibels units (mdB) as a function of \( z \) in the regions of the plots for \( z = 0-1.4 \) mm in (a), and \( z = 0-1.0 \) mm in (b). \( \Delta L_{\text{DUT}}(z = 1.4 \) mm) was 0.015 dB, which was the maximum value in this measurement, as shown in Fig. 3(a).

In the case of the ASEFC scheme, we measured \( P_{\text{out}} \) at \( z \), so that \( P_{\text{in}} \) at \( z \) was calculated using Eq. (3). \( P_{\text{out}} \) and \( P_{\text{in}} \) at \( z \) were denoted as \( P_{\text{out}}(z) \) and \( P_{\text{in}}(z) \), respectively. \( \Delta P_{\text{in}} \) of Eq. (2) was given by \( \Delta P_{\text{in}}(z) = P_{\text{in}}(z) - P_{\text{in}}(z = 0) \). The difference in \( P_{\text{out}} \) was denoted as \( \Delta P_{\text{out}}(z) = P_{\text{out}}(z) - P_{\text{out}}(z = 0) \). The absolute values of \( \Delta P_{\text{out}}(z) \) are plotted in Fig. 3(c) and (d). In the ASEFC scheme (Fig. 3(c)), the absolute value of \( \Delta P_{\text{out}}(z = 1.4 \) mm) of 1.23 dB was 82 times larger than \( \Delta L_{\text{DUT}}(z = 1.4 \) mm) of 0.015 dB. The excess noise in \( P_{\text{out}}(z) \) was estimated to be less than several times 0.001 dB. Then, the \( R_{\text{PM}} \) was set to 0.01 dB in this ASEFC scheme case. \( P_{\text{in}}(z = 0) \) was 15.787 dBm, which was 0.002 dB lesser than the input power, resulting in the maximum value of \( S \) (15.807 dBm). \( P_{\text{in}}(z) \) was calculated using Eq. (4), so that \( \Delta P_{\text{in}}(z) \) was derived from the relation \( \Delta P_{\text{in}}(z) = P_{\text{in}}(z) - P_{\text{in}}(z = 0) \). Moreover, \( \Delta L_{\text{DUT}} \) and \( S \) were derived using Eqs. (2) and (5), respectively. \( \Delta L_{\text{DUT}}(z) \) is shown as a function of \( z \) in Fig. 3(e) and (f). \( S \) as a function of \( z \) \( (S(z)) \), decreased with \( z \) from \( S(z = 0 \) mm) = 89.8, to \( S(z = 1.4 \) mm) = 67.3. The OPR at \( z \) \( (R_{\text{ASEFC}}(z)) \) was given by \( R_{\text{ASEFC}}(z) = R_{\text{PM}} / S(z) \). Therefore, \( R_{\text{ASEFC}}(z) \) was 0.00011 dB (0.11 mdB) at \( z = 0 \) mm, and 0.00014 dB (0.14 mdB) at \( z = 1.4 \) mm. As can be seen in the plots of Fig. 3(c) and (d), there was no random time variation or fluctuation in \( P_{\text{out}}(z) \) which is larger than 0.01 dB. Therefore, the time variation in \( P_{\text{outDUT}} \) was evaluated to be less than within 0.00014 dB in this measurement.

4 Conclusion
We proposed a novel optical power measurement scheme, named the ASEFC scheme, to significantly improve the OPR, compared with that of the conventional scheme. Furthermore, we proposed a simple analytical function which expressed the relationship between \( P_{\text{in}} \) and \( P_{\text{out}} \); thus, we succeeded in calculating \( P_{\text{in}} \) from the measured value of \( P_{\text{out}} \) in a systematic manner. The OPR characteristics of the ASEFC scheme were experimentally clarified by measuring the loss variation of the tested VOA. The OPRs were less than 0.00014 dB, and the sensitivities were more than 67, at a display resolution of 0.01 dB for the power meter.

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