Scattering Parameter Characterization of Microwave Optoelectronic Devices and Fiber-Optic Networks

Stavros Iezekiel, Christopher M. Snowden, and Michael J. Howes

Abstract—**A microwave fiber-optic network analyzer test set is proposed that will allow the application of two-port calibration theory to the measurement of optical and optoelectronic components in high frequency fiber-optic links. Formulae for the optoelectronic calibration are presented, and a unified approach to optical and optoelectronic two-port calibration theory is covered.**

I. Introduction

As the popularity of microwave fiber-optic links increases, the efficient measurement of fiber-optic and optoelectronic S-parameters will be vital to the overall design process [1]. The conventional test set-up for measuring the frequency response and return loss of a laser diode is shown in Fig. 1. The laser diode–photodiode (LD–PD) link constitutes a unilateral microwave network. Assuming that the optical path provides perfect transmission of the microwave signal, the measured S_{21} of the link is the product of the LD and PD frequency responses. If the PD is calibrated independently (using an optical heterodyne method [2] for example), the LD frequency response can be calculated. Curtis and Ames [1] have also used this test set-up to measure the transmission parameters of fiber-optic components, although the unilateral nature of the LD and PD necessitates reversal of the optical device under test (DUT) if the reverse transmission parameter is required. The optoelectronic isolation of the LD also prevents single-port measurement of the S_{11} and S_{22} parameters of the optical DUT. This is remedied by using a −3-dB fiber-optic directional coupler as shown in Fig. 2. Again, reversal of the DUT is required for measuring S_{22}, and a matched optical load must be used. Furthermore, the calibration of the set-up relies on offset shorts and a matched load of known quality [1].

This letter indicates that the need to have four distinct set-ups to obtain all four optical S-parameters can be obviated by using nonunilateral optoelectronic error networks (Fig. 3). In such a network, forward (electrical to optical) and reverse (optical to electrical) transmission is allowed; the circulator separates the incident and reflected electrical power waves. The advantage of this approach is that the two-port calibration methods in [3] can be employed in the optical and optoelectronic regimes.

Manuscript received April 24, 1991.

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IEEE Log Number 9102351.

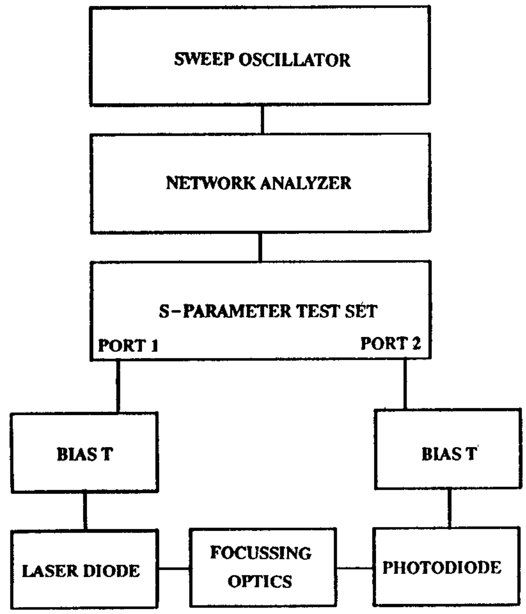

Fig. 1. Measurement system for obtaining the frequency response of a laser diode. Transmission parameter measurements of an optical DUT can also be performed once the LD–PD pair is calibrated.

II. Optical and Optoelectronic Calibration

Consider the cascade of nonunilateral electrical, optoelectronic and optical two-ports in Fig. 4 that is connected to network analyzer ports 1 and 2. Calibration of this network at planes P_1 and P_4 using a conventional microwave technique such as thru-reflect-line (TRL) [4] will provide error corrected measurements of an electrical DUT connected between P_1 and P_4. One can also calibrate the analyzer between P_2 and P_3 using an optical analog of the various methods described in [3]. For example, the line-line-network (LLN) method would use the following standards, denoted by **O1**, **O2**, and **O3**. **O1** and **O2** would be differing lengths of optical fiber with a refractive index referenced to that of the test set fiber. **O3** would be designed to be symmetrically reflecting, and so a length of fiber with a refractive index different to that of **O1** would be chosen. Ideally, **O3** should be highly reflecting. Compared with the standards required in [1], **O1**–**O3** are easily realizable and commercially available.

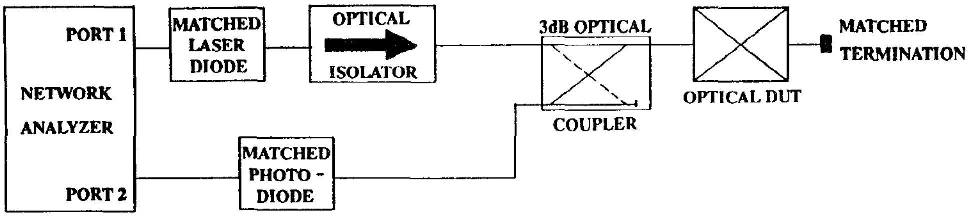

Fig. 2. Optical reflection parameter measurement configuration.

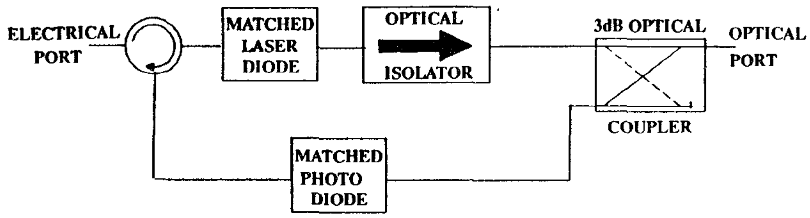

Fig. 3. Possible implementation of a nonunilateral optoelectronic two-port. Input port is electrical, the output optical.

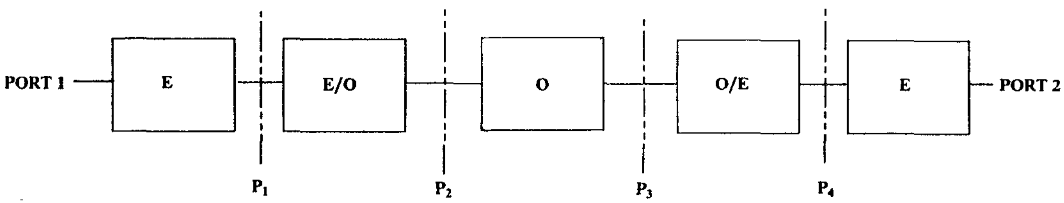

Fig. 4. Generalized microwave fiber-optic link, consisting of electrical (**E**), optical (**O**) and optoelectronic two-ports (**E/O** and **O/E**). **E/O** is identical to Fig. 3, while **O/E** is formed by reversing Fig. 3 (i.e., the input port is optical, the output electrical).

In particular, the reflection calibration [1] required specially fabricated offset reflects and matched loads. The magnitude and phase of the reflection coefficients of the standards also had to be fully known, and this required an independent measurement of these parameters. This contrasts with the proposed technique, which uses fiber transmission line standards; the fabrication of reflects is circumvented. In addition, the flexibility of optical fiber permits the use of a long length to construct a highly attenuating standard for **O2**. Hence the bandwidth limitations [3] of the microwave LLN method are avoided. At lower frequencies, the microwave transmission lines tend to be too long, and at higher frequencies they may exhibit periodically repeating ranges of unreliable calibration.

An important point to note is that the optical calibration procedure can also calibrate the network analyzer between P_1 and P_3, allowing optoelectronic two-port measurements to be made. In this case, the standards **EO1**–**EO3** are formed by cascading the optoelectronic network **E/O** with **O1**–**O3** in turn. This procedure, therefore, is physically identical to the optical calibration except for the definition of the standards and calibration planes. Using the same notation as Soares *et al.* [5] and optical LLN standards to form the optoelectronic standards, the de-embedded wave cascading matrix of the optoelectronic DUT is:

where

$$T'_1 = \left(m'_{11} - \bar{d}m'_{12} - \bar{b}m'_{21} + \bar{b}\bar{d}m'_{22}\right)\left[(\bar{a} - \bar{b})(\bar{c} - \bar{d})\right]^{-1}$$

$$T'_2 = \left(-m'_{11} + \bar{c}m'_{12} + \bar{b}m'_{21} - \bar{b}\bar{c}m'_{22}\right)\left[(\bar{a} - \bar{b})(\bar{c} - \bar{d})\right]^{-1}$$

$$T'_3 = \left(-m'_{11} + \bar{d}m'_{12} + \bar{a}m'_{21} - \bar{a}\bar{d}m'_{22}\right) \cdot\left[(\bar{a} - \bar{b})(\bar{c} - \bar{d})\right]^{-1}$$

$$T'_4 = \left(m'_{11} - \bar{c}m'_{12} - \bar{a}m'_{21} + \bar{a}\bar{c}m'_{22}\right)\left[(\bar{a} - \bar{b})(\bar{c} - \bar{d})\right]^{-1}$$

$$S' = S_{22,\mathrm{EO}1}\left(S_{12,\mathrm{EO}1}S_{21,\mathrm{EO}1}\right)^{-1}$$

$$ps = \left(\bar{c} + S_{22,\mathrm{M}1}\right)S_{21,\mathrm{EO}1}\left[S_{21,\mathrm{M}1}(\bar{c} - \bar{d})\right]^{-1}$$

$$kr = \left(\bar{d} + S_{22,\mathrm{M}1}\right)\left[S_{21,\mathrm{M}1}(\bar{d} - \bar{c})S_{12,\mathrm{EO}1}\right]^{-1}$$

m'_{ij} are the measured elements of the wave cascading matrix of the DUT, $S_{ij,\mathrm{M}1}$ are the measured S-parameters of **EO1** and $S_{ij,\mathrm{EO}1}$ are the actual S-parameters of **EO1**. $\bar{a}$, b, $\bar{c}$ and $\bar{d}$ are functions of the measured S-parameters of **EO1** and **EO2** (see [5] for details of the general calibration theory). The constants pr and ks can be related to each other by measuring the third standard **EO3**:

$$\frac{ks}{pr} = \frac{S_{11,\mathrm{M}3} - \bar{c}S_{12,\mathrm{M}3} - \bar{b}S_{21,\mathrm{M}3} + \bar{b}\bar{c}S_{22,\mathrm{M}3}}{S_{11,\mathrm{M}3} - \bar{d}S_{12,\mathrm{M}3} - \bar{a}S_{21,\mathrm{M}3} + \bar{a}\bar{d}S_{22,\mathrm{M}3}},$$

$$\mathbf{R}_{T\,\mathrm{dut}} = \begin{bmatrix} (kr)^{-1}T'_1 & (ks)^{-1}T'_2 \\ -(kr)^{-1}S'T'_1 - (pr)^{-1}T'_3 & -(ks)^{-1}S'T'_2 + (ps)^{-1}T'_4 \end{bmatrix},$$

where $S_{ij,M3}$ are the measured S-parameters of **EO3**. An estimate of the phase of $S_{11,EO3}$ (or $S_{22,EO3}$) to within $\pm 90°$ of its true value is required to eliminate the sign ambiguity of the values of $S_{11,DUT}$ and $S_{22,DUT}$. These equations apply to the case of the input of **E/O** being matched to the electrical reference impedance.

III. Discussion and Conclusion

As with any self-calibration procedure [3], the first standard is assumed to be fully known. With the optical and microwave calibrations, the standards are passive. It is relatively easy to deduce their transmission parameters from their physical lengths and the calibration measurements for example. Indeed, a through connection can provide the first standard, and this is the simplest known two-port [3]. Unfortunately, the optoelectronic calibration relies on the network in Fig. 3 to form the standards. Nevertheless, the optical calibration provides some information on the S-parameters of the optoelectronic standards. Network **E/O** is one of the error networks in this process, and the optical calibration provides $S_{11,E/O}$, $S_{22,E/O}$ and the product $S_{12,E/O}S_{21,E/O}$. In addition, the S-parameters of **O1–O3** can be measured. However, $S_{12,E/O}$ (or $S_{21,E/O}$) must be measured independently if the optoelectronic DUT is to be fully de-embedded. An optical heterodyne method can provide $|S_{12,E/O}|$, which means that only the magnitudes of $S_{12,DUT}$ and $S_{21,DUT}$ can be determined.

Although the optoelectronic calibration requires independent measurement of $|S_{12,E/O}|$, there are still significant advantages in adopting the overall approach proposed here. Firstly, the set-up in Fig. 4 can be used to calibrate optical devices with a set of easily realisable standards. Secondly, the method exploits the capability of modern network analyzers to perform two-port S-parameter measurements with a single connection of the DUT in the test set. This greatly reduces the number of operator steps. Finally, provided one of the optoelectronic networks (say **E/O**) is independently calibrated, an optoelectronic calibration can be performed simultaneously. Once completed, this allows any optoelectronic two-port (including LD's and PD's) to be measured. The proposed technique therefore represents a unified approach to the characterization of optical and optoelectronic two-ports.

Acknowledgment

The authors would like to thank Dr. R. D. Pollard at the University of Leeds for his comments on the manuscript, and for suggesting that it should be written.

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