Simulation and Implementation of Lightwave Component Characterization Using a Bilateral Electro-Optic Network

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***Abstract*— The simulation and implementation of a bilateral electro-optic network has been demonstrated. The advantage of the proposed network is that it can be used as a black box to convert a microwave network analyzer into a two-port lightwave network analyzer. Simulations have been carried out to determine the sensitivity of the bilateral network to optical reflections. Measurement results on one-port optical structures are more accurate than those obtained with commercial lightwave analyzers and indicate the viability of this approach for full two-port lightwave measurements.**

***Index Terms*— Calibration, microwave measurements, microwave photonics, optical measurements.**

I. INTRODUCTION

THE increasing use of microwave fiber-optic links has created a need for accurate small-signal characterization of the constituent components. These can be classified into four categories depending on whether the type of signal at the input and output ports is electrical (E) or optical (O) [1]. A decade ago, the microwave modulation response of lightwave components was measured by simple configurations involving high-speed laser diodes and photodiodes connected to microwave network analyzers. One configuration determined the transmission response of E/O, O/E, and O/O two-ports, and another with the addition of an optical coupler determined one-port reflection measurements of O/O components [2]. Curtis and Ames [3] described calibration and de-embedding techniques for both the transmission and reflection configurations. Lightwave test sets and component analyzers are now commercially available [4], [5], but they still employ the same basic topologies proposed in [2]. Consequently, many distinct measurement configurations and corresponding calibration techniques must be used if the full range of lightwave components is to be characterized. Recently, a bilateral test set [6] has been developed which allows optical two-port calibrations to be applied, but it is only capable of measuring O/O components.

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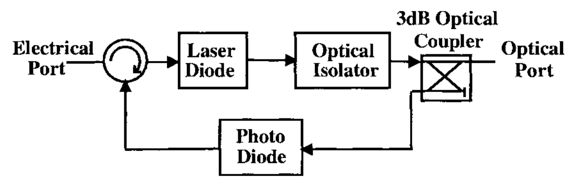

Fig. 1. Bilateral lightwave network. After [7].

A unified approach to circumvent the unilateral nature of the previous lightwave test sets was proposed by Iezekiel *et al.* [7], but it was not simulated or implemented. The technique relies on using the bilateral network (shown in Fig. 1) to extend the microwave network analyzer to perform lightwave component analysis. If the S-parameters of the bilateral electro-optic network are time invariant and can be pre-measured and stored, then not only can the E/E parameters be measured, but the E/O, O/E, and O/O parameters can also be obtained.

The work presented in this paper can be extended to cover the proposal in [7], however, the emphasis here is on the application to optical one-port measurements. The sensitivity of the bilateral network to optical reflections is fully analyzed and optical one-ports are measured using the network. In this way, the sensitivity, and hence, the potential usefulness of the bilateral network as a two-port lightwave test set can be assessed.

II. SIMULATION

Simulations were carried out to determine the sensitivity of the bilateral network of Fig. 1 to changes in optical reflections. To make the simulations realistic, typical S-parameter values of commercially available components were used. Hence, the poor isolation properties of the microwave circulator and the unilateral nature of the laser and the photodiode were all included in the simulations.

The microwave reflection coefficient at Port 1 of the microwave network analyzer is denoted by S_{11M}. It depends on both the components of the bilateral network and the optical load connected to the optical coupler. The reflection coefficient of the optical load is to be de-embedded from S_{11M}. The sensitivity at the microwave port of the bilateral network to changes in optical reflection coefficient, Γ_{optical}

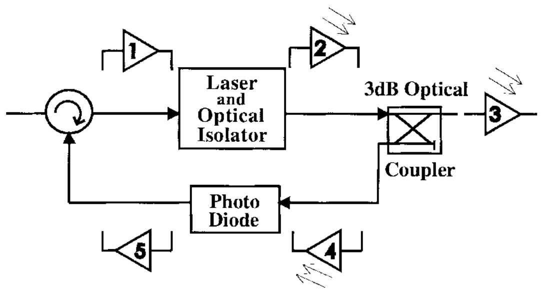

Fig. 2. Bilateral network showing the possible different positions for an amplifier.

was determined by evaluating the following expressions:

$$\text{Magnitude Sensitivity} = \frac{S_{11M,n+1} - S_{11M,n}}{\Gamma_{\text{optical},n+1} - \Gamma_{\text{optical},n}} \tag{1}$$

$$\text{Phase Sensitivity} = \frac{\angle S_{11M,n+1} - \angle S_{11M,n}}{\angle \Gamma_{\text{optical},n+1} - \angle \Gamma_{\text{optical},n}} \tag{2}$$

where $\Gamma_{\text{optical},n+1}$ and $\Gamma_{\text{optical},n}$ are two consecutive values in the range $0, 0.05, \cdots, 1$, $S_{11M,n+1}$ and $S_{11M,n}$ are the corresponding values of the microwave reflection coefficients of the network, and $\angle$ indicates the phase of the relevant parameter.

Initial simulations demonstrated that both the magnitude and phase sensitivities are lower than the those of the ideal case where a unit change in optical reflection will produce a unit change at the microwave ports. This reduction in sensitivity is due to the poor isolation of the microwave circulator and the approximately 60-dB total electro-optic and optoelectronic conversion losses in the laser and the photodiode, respectively.

The low sensitivity of the network may be overcome by the addition of amplifiers. To determine the best amplifier position for the highest sensitivity, simulations of the network with a single amplifier at any one of the locations shown in Fig. 2 were conducted. The amplifiers in positions 1 and 5 are electrical amplifiers, whereas the other three are optical amplifiers. Generic broad-band amplifiers were considered for both the electrical and the optical cases. Erbium-doped fiber amplifiers (EDFA's) will be preferred where available over semiconductor optical amplifiers (SOA's) for the optical amplifiers, because of their low noise figure and high gain properties. An optical isolator and an optical filter are needed at the output of the optical amplifier to make it unilateral and to reduce the spurious noise.

Fig. 3 shows the sensitivity variation as a function of amplifier gain. The variation in the shape of the curves is obtained because of the unilateral nature of the laser and the photodiode and their position in the bilateral network. As a result of this variation, the choice of the best amplifier position depends on the sensitivity required. For example, at a 20-dB unilateral gain, the optical amplifiers perform better than the electrical amplifiers and an amplifier in position 4 gives the best sensitivity. This is because the signal levels in the optical domain are much lower and, hence, optical amplification will bring the signal level of small reflections up to the noise

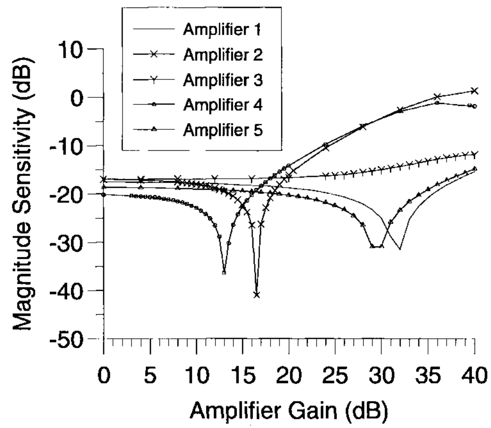

Fig. 3. The effect of the position of the amplifier on network. Amplifier gain versus magnitude sensitivity.

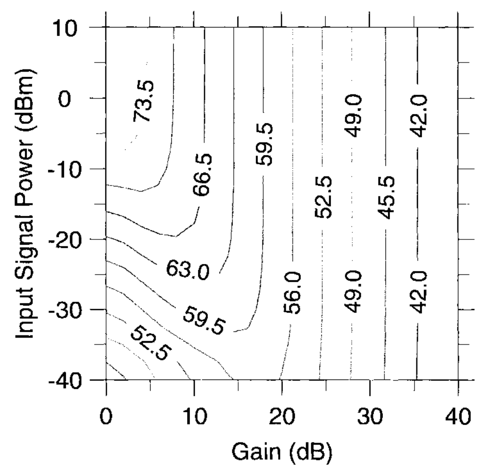

Fig. 4. Contours of SNR in decibels of an optical receiver with variation in input signal power at the optical amplifier and the optical amplifier gain.

floor of the photodiode. An optical amplifier in position 2 has the disadvantage that it is more likely to be operating in the saturation region, while one in position 3 requires a bilateral amplifier which increases the amplified spontaneous emission (ASE) noise power [8].

The simulated results of the signal-to-noise ratio (SNR) of the photodiode when an optical amplifier is included are shown in Fig. 4. Signal-spontaneous beat noise and spontaneous-spontaneous beat noise from the optical amplifier were considered in addition to the quantum noise of the photodiode [9]. For a constant gain, the degradation in SNR increases with increasing input signal power, and for a constant input signal power it increases with increasing optical gain. However, the gain of a real optical amplifier decreases with increasing power. Hence, these two cancel with reduced effect on the receiver SNR. Overall, the ability to detect small reflections by including an amplifier more than compensates for any SNR degradations.

III. Experiments

In the implementation, the microwave circulator is the component with the most significant bandwidth limitation

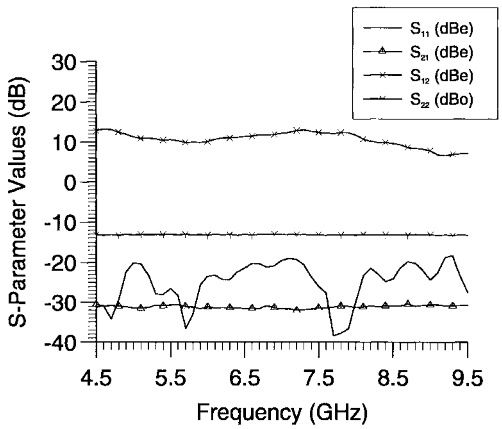

Fig. 5. Measured S-parameters of the bilateral network.

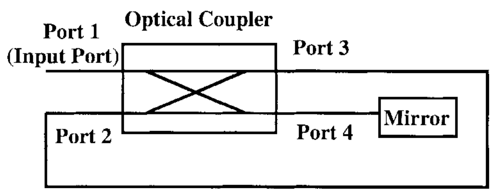

Fig. 6. Structure of a recirculating delay line terminated in a mirror.

(4.5–9.5 GHz). An isolator to reduce the reflections at the laser output is necessary to enhance the repeatability of the measurements. The laser used in these experiments (Ortel 3541B) has an in-built isolator and operates at 1.31 μm.

The S-parameters of the bilateral network are determined by implementing calibrated measurements on an HP8703A lightwave component analyzer and are saved. These parameters as measured are shown in Fig. 5. S_{21}, S_{12}, and S_{22} of the bilateral network have an almost flat response in the passband, whereas S_{11} has a variation greater than 10 dB. After these S-parameters are measured and stored in memory, the optical reflection coefficient (Γ_L) is calculated by de-embedding from the calibrated microwave reflection measurements.

Two structures were used to test the capability of the bilateral network for de-embedding optical reflections. The first is a mirror at the end of a fiber patch cord. This structure has a reflection of 76%. The other is a recirculating delay-line configuration terminated in a mirror as shown in Fig. 6. This structure has an optical reflection coefficient which varies periodically with frequency. Fig. 7 shows that the dynamic range of the optical reflection coefficient of the structure increases almost monotonically as the coupling ratio of the optical coupler increases. The coupler used in the experiment has a coupling ratio of 0.65, resulting in an overall dynamic range for the structure of around 5 dB.

Fig. 8 compares the experimental results obtained from the de-embedding procedure with that obtained from the HP8703A analyzer and the theoretical predictions. The results obtained with the bilateral network closely follow the theoretical predictions. Fig. 8(a) shows that only this method indicates loss for the −1.2-dB mirror, whereas the HP 8703A shows a gain of 0.4 dB. Fig. 8(b) demonstrates that the bilateral

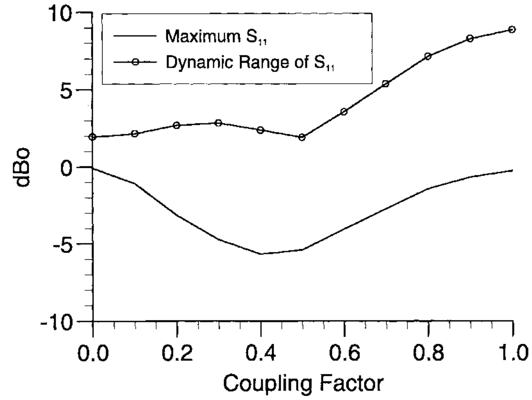

Fig. 7. Simulated results of the maximum value and the dynamic range of the optical reflection coefficient of the recirculating delay-line structure as a function of the coupling factor of the optical coupler.

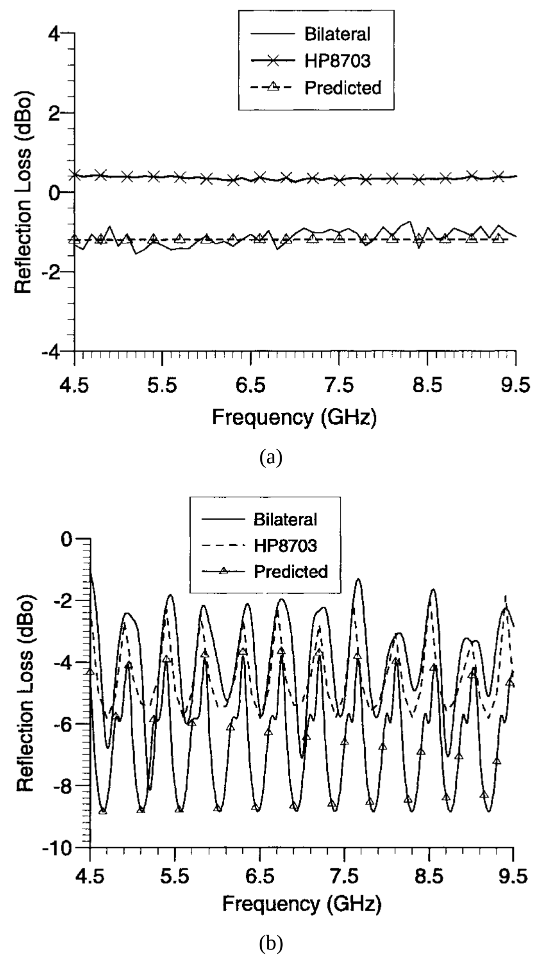

Fig. 8. De-embedded results of the (a) mirror and (b) recirculating delay line terminated in a mirror.

network is also capable of accurately following trends in the optical reflections. The lightwave component analyzer measurements are smoother than the responses obtained with the bilateral network, although the better performance of the former is probably due to the fact that the feedback circuits necessary to stabilize the laser power and temperature in the commercial instrument are not provided for the bilateral network.

IV. Conclusion

A bilateral electro-optic network is used to extend the performance of conventional microwave network analyzers to perform lightwave component analysis by implementing a de-embedding procedure. Theoretical simulations and experimental work on optical one-ports have demonstrated the viability of this approach for lightwave component characterization. The measurements on one-port optical components show that the results obtained with the bilateral network appear more accurate compared to those obtained with commercial lightwave component analyzers. A repeatability of −25 dB has been achieved for optical one-ports. This compares with −35 dB repeatability obtainable with commercial lightwave component analyzers.

The bandwidth constraint presented by the microwave circulator can be overcome with the use of quasi-circulator modules [10]. Moreover, a broad-band directional coupler (which is essentially a circulator with poor isolation) can be used to extend the frequency range below 1 GHz and also to make the configuration broad-band. An optical circulator can be used instead of the optical coupler to increase the sensitivity at the microwave ports. The measurement repeatability can be improved by including feedback circuits for laser power stability, while the sensitivity can be enhanced by including amplifiers or by including an external modulator and operating the laser in a continuous-wave mode. The advantage of the proposed network is that it can potentially be used for the implementation of two-port optical and optoelectronic calibration with the help of microwave calibration.

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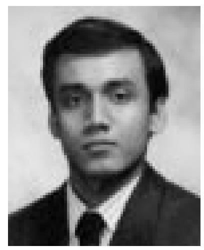

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Stavros Iezekiel (S'88–M'90), for a photograph and biography, see this issue, p. 1461.