Recent developments in lightwave network analysis

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The widespread use of photonic systems having microwave modulation bandwidths, coupled with the inclusion of photonic components in microwave and millimetre-wave systems, is creating a demand for efficient characterisation techniques. In particular, new tools will be required for the measurement of fundamental quantities such as the microwave frequency response, bandwidth, gain and return loss of microwave photonic components. However, existing lightwave measurement techniques are primitive when compared with conventional RF and microwave network analysis. This paper provides a review of the theory and techniques used for the small-signal characterisation of microwave photonic components. State-of-the-art architectures for lightwave network analysers and the corresponding two-port calibration techniques are described.

Microwave photonic components are finding an increasing number of applications in the optical generation[1], distribution[2] and processing[3] of microwave signals, fibre-radio picocellular communication systems[4], antenna beam forming[5] and optical control of microwave devices[6]. This has brought about a corresponding need for accurate lightwave component characterisation, which will also be of importance in the development of microwave photonic integration technologies[7].

A fibre-optic link may typically be used to transmit multi-gigabit per second data, in which case figures of merit such as bit error ratio (BER) for a given data rate are usually quoted in both the specification and link characterisation stages[8]. However, the BER and measurements derived from it only give an indication of the overall system performance, whereas the limitations on system performance are due to the individual lightwave components and their interaction with one another. Even within digital optical-fibre systems, components such as laser diodes still behave as analogue devices. Moreover, there are a growing number of microwave photonic systems which are purely analogue (fibre links for remote location of antennas and subcarrier multiplexing[9] are two examples) and the BER is not relevant for these.

Given that lightwave components in many applications are operating at microwave frequencies, figures of merit related to their microwave counterparts take on added importance in helping to design individual

The authors of this paper were awarded the 1999 IEE Measurement Prize for their pioneering work on two-port lightwave network analysers and self-calibration techniques. The picture shows Professor Roger Pollard (centre) and Dr. Stavros Iezekiel (right) accepting the award from Alastair Macdonald, Director General of Industry at the DTI.

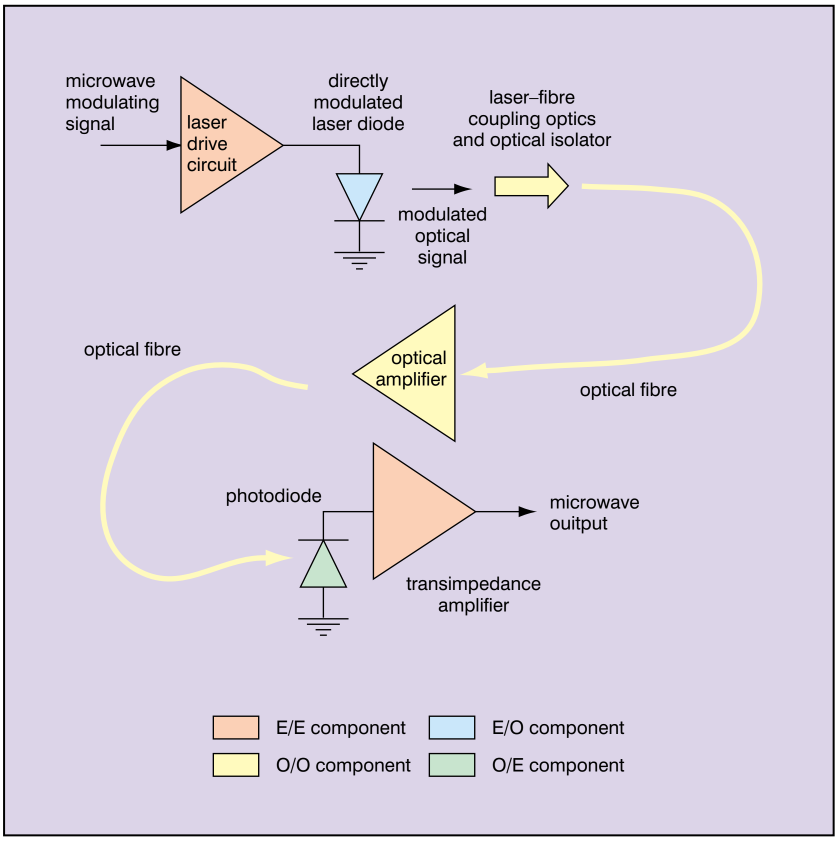


Fig. 1 A microwave fibre-optic link

lightwave components and then optimising the overall system performance. Laser diodes, for example, have a low input impedance, which necessitates matching in order to eliminate reflections that can cause signal distortion and reduce conversion efficiency. In addition, their intensity modulation frequency response often limits the overall bandwidth of a directly modulated fibre link. Moreover, this modulation response can be degraded by optical reflections, which is the reason for optical isolators being used in many laser diode transmitter modules. Measurements of return loss and insertion loss against frequency are therefore needed by the designer of a microwave photonic system in order to assess the impact of a directly modulated laser diode on the overall system's microwave performance and vice versa. They are also required to extract the parameter values of microwave circuit models[10] of components such as laser diodes.

Table 1: Types of lightwave component (after Reference 8)

	Electrical output	Modulated optical output
Electrical input	*E/E components* • microwave amplifiers • microwave filters • impedance matching networks • coaxial cables	*E/O components* • laser diodes • electro-optic modulators
Modulated optical input	*O/E components* • PIN photodiodes • avalanche photodiodes • optically controlled microwave devices, e.g. optoelectronic self-oscillating mixers	*O/O components* • optical fibre • optical isolators • optical attenuators • optical directional couplers • optical fibre amplifiers

However, these considerations apply not just to laser diodes but to the full range of lightwave components used in a system. Such measurements fall under the umbrella term of lightwave network analysis, and the corresponding measurement systems are known as lightwave network analysers. When purely electronic components are considered, the more familiar terms of microwave network analysis and microwave network analysers are applied.

Definitions

Consider a typical microwave photonic system such as a high-speed fibre-optic link (Fig. 1). The constituent two-port components can be classified according to the type of signal present at the input and output ports. These are either electrical (E) signals at microwave frequencies or optical signals (O) whose power is modulated at microwave frequencies. (Modulation of the optical wavelength itself will not be covered here.) Lightwave components can therefore be identified as E/E, E/O, O/E or O/O and examples of each type are given in Table 1.

Despite the mix of electrical and optical ports, all lightwave components manipulate microwave signals, either at baseband or when modulated onto an optical carrier, and therefore possess a microwave frequency response. While the concept of a microwave frequency response for a linear E/E component is straightforward (allowing the use of microwave scattering parameters for characterisation, see Fig. 2), the concept requires clarification for O/O components. By definition, these act on optical signals, typically at wavelengths of 1·3 μm or 1·55 μm, and can be described by optical scattering parameters[11] at a fixed wavelength. This picture is valid for unmodulated optical signals. However, when a microwave sinusoid is applied to the input of E/O components such as laser diodes and Mach–Zehnder modulators, the optical output power is modulated at the microwave frequency. In other words, the E/O conversion process can be thought of as double-sideband intensity modulation of an optical carrier by a microwave envelope. O/E conversion is the reverse process, i.e. demodulation by an optical detector that ideally produces a microwave current that is the square of the detected electrical field.

A microwave signal is therefore superimposed on an optical carrier as a pair of sidebands, which, for a typical optical frequency of the order of 200 THz, are very close to the optical carrier. With the usually valid assumption of low Q optical components, the microwave sidebands are subjected to the same phenomena (e.g. attenuation and dispersion) as the optical carrier. Hence the microwave frequency response of an O/O component relates the output microwave envelope of a modulated optical carrier to the input microwave envelope. In contrast, the microwave frequency response of an E/O two-port relates the output microwave envelope to the input baseband microwave signal, and for an O/E component the output baseband microwave signal resulting from an input microwave envelope.

These considerations allow scattering parameters (*S*-parameters) to be defined for all four types of two-port lightwave component (Fig. 2). However, caution must be exercised because of the differences between electrical and optical power and the question of nonlinearity that arises.

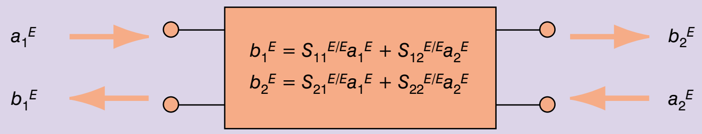
Principles of lightwave network analysis

Lightwave network analysis is defined as the measurement of the lightwave *S*-parameters of E/E, E/O, O/E and O/O two-ports. This allows the small-signal microwave characteristics (such as modulation frequency response, transmission gain/loss, return loss and phase delay) and a wide variety of other parameters to be obtained from measurements of the *S*-parameters (Table 2).

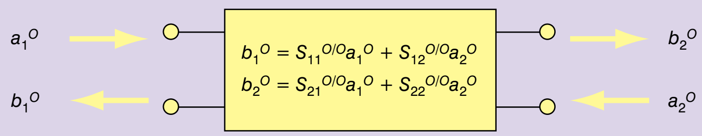
Although characterisation of

Table 2: Measurements derivable from *S*-parameters (after Reference 8)

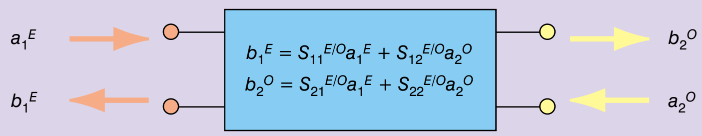
Transmission	Reflection
Insertion loss/gain Frequency response • modulation bandwidth • flatness • slope responsivity (E/O and O/E) Time domain analysis • rise time • pulse dispersion Delay Length Insertion modulation phase Refractive index Reflection sensitivity (E/O)	Return loss Impedance (electrical) Reflectometry • electrical (time domain) • optical (frequency domain) Delay Length



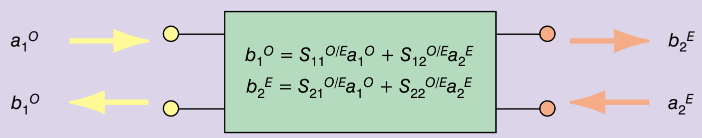
- A linear E/E two-port may be characterised using *S*-parameters (scattering parameters).
- The variables a_1^E, a_2^E represent incident travelling power waves at ports 1 and 2, respectively, while b_1^E, b_2^E represent reflected travelling power waves. These variables have the dimensions of √(electrical power), i.e. they are directly proportional to the microwave current.
- $S_{11}^{E/E}$ and $S_{22}^{E/E}$ represent the input and output reflection coefficients, while $S_{21}^{E/E}$ and $S_{12}^{E/E}$ are the forward and reverse transmission coefficients.



- In the case of O/O two-ports, the variables a_1^O, a_2^O, b_1^O, b_2^O represent optical power waves modulated at the microwave frequency. These are chosen to have dimensions of (optical power), i.e. they also have dimensions of √(electrical power).



- For an E/O two-port $s_{21}^{E/O}$ represents the electro-optic conversion process, i.e. the conversion of microwave current to modulated optical power. In the case of a laser diode, provided its peak-to-peak modulation current does not exceed the limits of the linear light–current curve, linearity is guaranteed in the relationship between microwave modulation current and the output modulated optical power. Under these circumstances, $|s_{21}^{E/O}| = \eta$, where η is the differential efficiency of the laser diode.



- For an O/E two-port $s_{21}^{O/E}$ represents the photodetection process, i.e. the conversion of optical power to microwave current. In the case of a photodiode, provided it obeys a square law relationship, then the photocurrent will be directly proportional to the square of the incoming electric field's magnitude. Hence linearity is ensured in the relationship between input modulated optical power and the photogenerated microwave current. Under these circumstances $|s_{21}^{O/E}| = R$, where *R* is the photodiode responsivity.
- Most E/O and O/E components do not have reverse transmission; however, for those that do, it can be seen that $s_{12}^{E/O}$ and $s_{12}^{O/E}$ correspond to photodetection and electro-optic conversion, respectively.

Fig. 2 *S*-parameter definitions for lightwave components

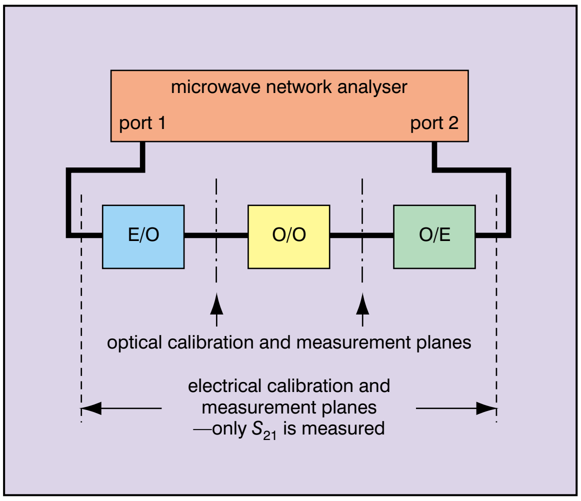


Fig. 3 Transmission measurement configuration

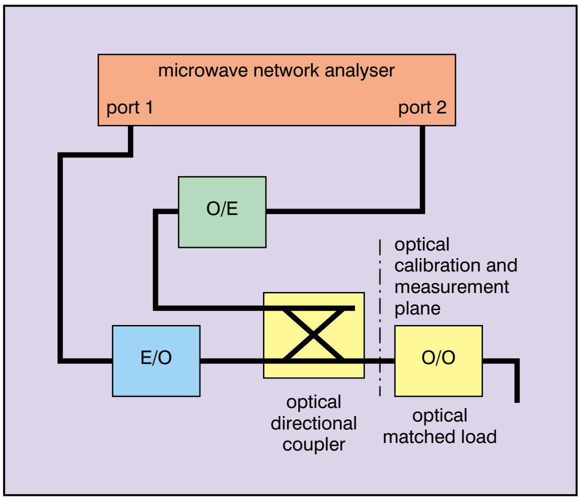


Fig. 4 Reflection measurement configuration for O/O components

E/E components is readily carried out with microwave vector network analysers (VNAs), for which a wealth of two-port calibration techniques is available[12–16], corresponding measurement techniques for E/O, O/E and O/O two-port parameters are less developed. For example, the industry-standard lightwave network analyser[17] requires two measurement configurations and up to four distinct calibrations to measure all four types of lightwave components. Moreover, the lightwave calibrations are simple normalisation procedures, which will result in measurement errors unless all parts of a system are well matched. In this respect, contemporary lightwave test sets and the calibration of them have not progressed much beyond the work described in References 17–19, which can be regarded as the first generation of lightwave network analysis.

This relatively primitive state of affairs will be illustrated by examining the two main measurement configurations employed by commercial instruments. In the first, a cascade of E/O, O/O and O/E components can be regarded as an E/E two-port, the S-parameters of which can be measured with a conventional microwave network analyser (Fig. 3). Now, the majority of E/O and O/E components are unilateral in nature ($S_{12}^{E/O} = 0$, $S_{12}^{O/E} = 0$). In other words, photodetectors do not act as optical sources, and laser diodes do not normally photodetect. Moreover, if an E/O module (e.g. a laser diode) with an integral optical isolator is used, and negligible reflections from the optical input to the photodetector are assumed, then the measured S_{21} of the overall cascade is the product of the frequency responses of the laser diode, the optical two-port and the photodetector:

$$S_{21} = S_{21}^{E/O}\, S_{21}^{O/O}\, S_{21}^{O/E} = M_1$$

where M_1 is the S_{21} measured with a calibrated

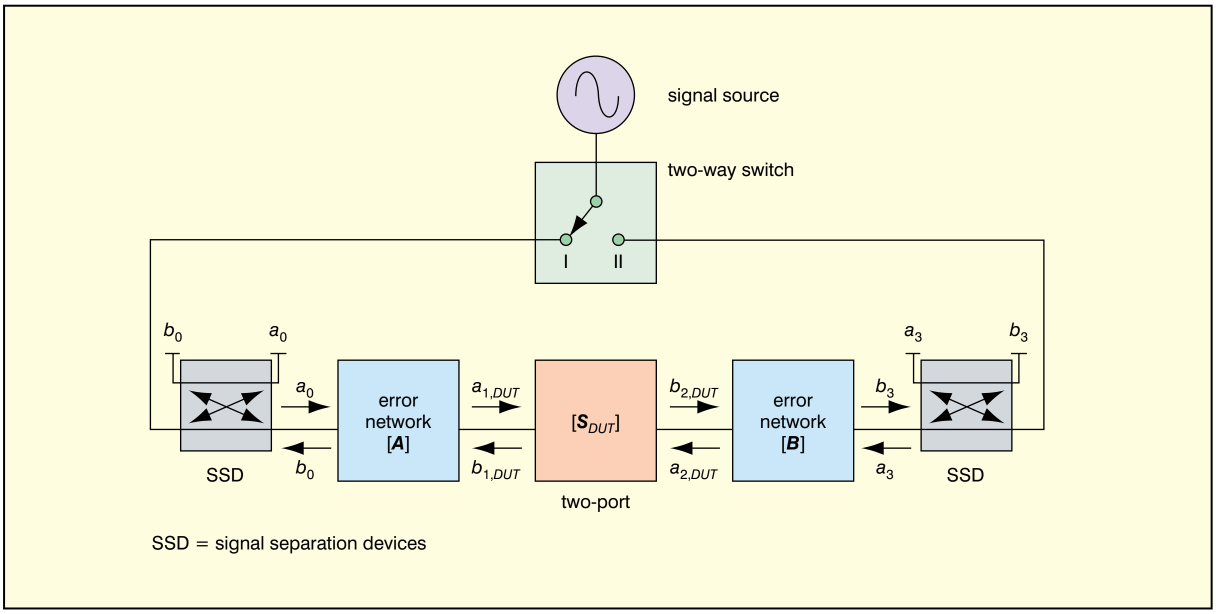


Fig. 5 Reduced error network model for a network analyser

microwave VNA. (Note that in this case the measured S_{11} and S_{22} of the cascade are equal to $S_{11}{}^{E/O}$ and $S_{22}{}^{O/E}$, respectively.) It is possible to measure independently the frequency response $S_{21}{}^{O/E}$ of a photodiode by using the optical heterodyne technique[20]. If a through connection is then made between the E/O and O/E two-ports by omitting the O/O device (which is mathematically equivalent to putting $S_{21}{}^{O/O} = 1$) then:

$$M_2 = S_{21}{}^{E/O}\ S_{21}{}^{O/E}$$

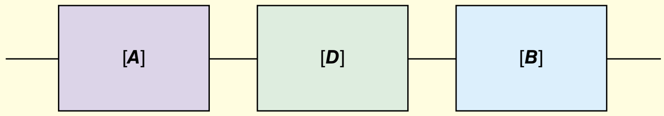
and the E/O response may be obtained directly:

$$S_{21}{}^{E/O} = M_2/S_{21}{}^{O/E}$$

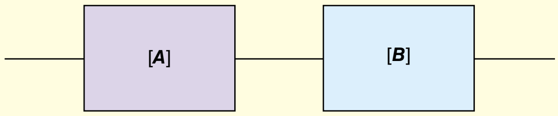
This configuration may also be used to obtain the transmission response of an O/O component, but without necessarily having to know $S_{21}{}^{O/E}$. Again, the system is calibrated using an O/O through connection. Inserting the O/O device under test (DUT), its forward transmission parameter is readily found:

$$S_{21}{}^{O/O} = M_1/M_2$$

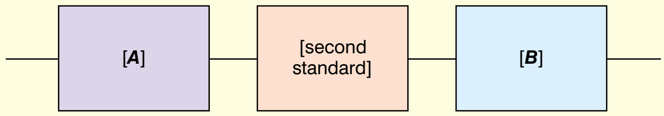
- If one considers a model of the errors in a network analyser, they can be incorporated into two error networks with transfer matrices [***A***] and [***B***], with [***D***] denoting the transfer matrix[13] of the device under test. Under this model, one can think of obtaining measurements [***M***] with an ideal network analyser: [***M***] = [***A***][***D***][***B***]



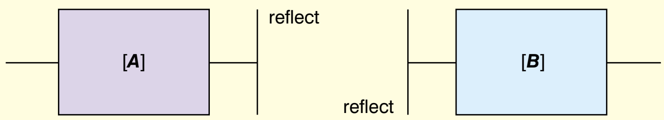
- However, what is desired is knowledge of [***D***]. It is therefore necessary to remove the effects of the error networks [***A***] and [***B***] in order to de-embed [***D***] from the measured result [***M***]: [***D***] = [***A***]$^{-1}$[***M***][***B***]$^{-1}$.
- De-embedding can be accomplished once the network analyser model above has been calibrated at the planes of the DUT. This involves substituting the DUT with a set of calibration standards (which usually number three); in the case of self-calibration procedures, using three or more standards to calibrate out the error networks results in an overdetermined set of equations, which allows one to use redundancy in specifying the calibration standards. Specifically, one need not know all the *S*-parameters of all the calibration standards.
- For example, the first standard is often chosen to be a through connection (T). This is the simplest standard that is fully known. (Its transfer matrix is simply the identity matrix.)



- Flexibility is then allowed in the choice of the second standard. One may choose from an attenuator (A), a matched load (M) or a transmission line (L), which in the optical domain would be an optical fibre. Moreover, not all the *S*-parameters of the second standard need be known: in the case of the A standard, the only requirement is that $S_{11} = S_{22} = 0$.



- This flexibility is extended into the third standard. One may choose from a reflect (R) or a symmetrical network (N). In the case of the reflect-standard, the value of the reflection need not be known. For optical calibrations, one may also include a Fresnel reflection (F). If a bare optical fibre is used to achieve the Fresnel reflection, it is possible to assume a known value of return loss (14 dBo) for the resulting standard F_K.



- Hence in the optical domain, for example, one may choose from twelve possible calibrations, which in general are denoted as T*xy*, and it is only necessary for the first standard (T) to be fully known.

Fig. 6 Priciples of two-port self-calibration and de-embedding

However, the unilateral nature of both E/O and O/E components necessitates reversal of the O/O DUT if the reverse transmission parameter $S_{12}{}^{O/O}$ is required. The unilateral behaviour of the E/O and O/E two-ports also prevents single-port measurement of the reflection properties ($S_{11}{}^{O/O}$ and $S_{22}{}^{O/O}$) of the O/O DUT. This shortcoming is remedied by using a separate configuration (Fig. 4) in which an optical directional coupler separates the incident and reflected signals. As before, reversal of the DUT is required. Furthermore, the calibration of this configuration by conventional methods would require the use of offset shorts and a matched load[21], the *S*-parameters of which must be known accurately. Moreover, these are components that to date are not commercially available and must be fabricated by the user.

To understand fully the limitations discussed above, it is instructive to consider briefly the architecture and operation of a microwave VNA. The systematic errors (i.e. those that can be removed by calibration) in a microwave VNA two-port measurement may be modelled by a four-port error network between the DUT and an ideal network analyser. Assuming cross coupling between the two measurement ports to be negligible, the four port error network can be further reduced to two equivalent two-port networks, one on each side of the measurement ports. This reduced block diagram is shown in Fig. 5. The cascade of error networks and DUT is similar in form to Fig. 3, with some important differences (in addition to the obvious one of this being a purely E/E set-up). Firstly, the error networks A and B are bilateral, that is they allow forward and reverse transmission. Secondly, allied with the use of a reversing switch, this allows all four *S*-

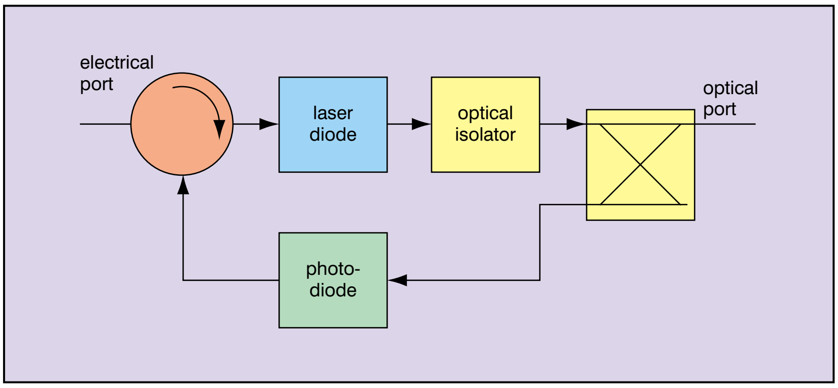


Fig. 7 A bilateral electro-optic network (BEON)

parameters of the DUT to be measured *in situ*. Not having physically to reverse the DUT is a significant benefit, but the overriding advantage of this architecture is the ability to implement self calibration procedures as explained in Fig. 6. The advantage of these techniques is that they exploit redundancies that result from having an overdetermined set of equations to solve (twelve measurements to determine eight terms). Consequently, detailed knowledge of all of the calibration standards' *S*-parameters need not be known. Indeed, only the first standard needs to be fully determined. This can be implemented as a through connection—the simplest two-port that can be defined.

Noting the similarity between the microwave VNA error network model (Fig. 5) and the configuration for measuring the transmission response of lightwave components (Fig. 3) suggests that the latter could be set up as an O/O network analyser in which the E/O and O/E two-ports act as error networks. However, this would only be possible if signals could flow in both the forward and reverse directions of the E/O-O/O-O/E cascade, and this in turn requires E/O and O/E two-ports that allow a two-way flow of signals. As noted earlier, laser diodes and photodiodes do not possess this attribute of bilateral behaviour.

A modular approach to lightwave network analysis

The limitations of first generation lightwave network analysis techniques can be overcome by using a modular approach[22–23] developed in the School of Electronic and Electrical Engineering at The University of Leeds. The key element of this technique is a bilateral electro-optic network (BEON) (Fig. 7), in which forward (electrical to optical) and reverse (optical to electrical) transmission is allowed. Incident and reflected *electrical* power waves are separated by the microwave circulator, while incident and reflected modulated *lightwaves* are separated by a directional coupler (although an optical circulator could be used instead). The advantage of this second generation approach to lightwave network analysis is that the two-port calibration and de-embedding methods developed for microwave networks can be employed in both the optical and optoelectronic regimes by using a pair of bilateral electro-optic networks as microwave-to-optical transducers, thereby significantly improving both speed and accuracy.

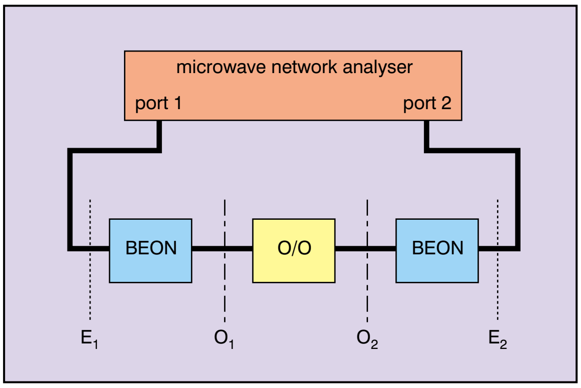


Fig. 8 Modular approach to lightwave network analysis using BEONs

Calibration of this network when used as part of a cascade connecting the ports of a microwave network analyser will yield error-corrected measurements of electrical, electro-optic and optical two-ports. This can be achieved using an optical analogue of the various microwave two-port calibrations (such as TRL, LRL, TAN) that have been developed[15]. As mentioned earlier, these techniques have the advantage that full knowledge of all of the calibration standards' *S*-parameters is not required. This type of redundancy is not achievable with direct calibration techniques such as the SOLT (short-open-load-through) or the offset shorts methods used in first generation approaches[20].

Consider the cascade of two BEONs and an O/O two-port that is connected between ports 1 and 2 of a microwave network analyser (Fig. 8). Calibration of this network at planes E_1 and E_2 using a conventional microwave technique such as through-reflect-line will provide error-corrected measurements of an electrical DUT connected between these planes. One can also calibrate the analyser between O_1 and O_2 using an optical analogue of the various methods described in Reference 15. An important point is that the optical calibration procedure can also calibrate the network analyser between E_1 and O_2 allowing E/O measurements (and also, if the DUT is reversed, O/E measurements) to be made. In this case, the E/O calibration standards are formed by cascading the left-hand BEON with the three optical standards in turn.

The performance of the bilateral electro-optic network has been simulated and measured[23], and it was shown that it could be used in a one-port optical measurement configuration with a 'blackbox approach'. A typical result is shown in Fig. 9*a*, where the network was used to measure the reflection coefficient of a mirror on the end of an optical-fibre patchcord. This structure has a reflection of 76%, and Fig. 9 compares the de-embedded results using the bilateral electro-optic network and a commercial lightwave component analyser. The latter erroneously indicates a gain of 0·4 dBo because of the uncalibrated mismatches, whereas the former correctly shows a reflection loss of 1·2 dBo. Fig. 9*b* gives a comparison between the two instruments for measurements on a recirculating optical-fibre delay line terminated in a mirror[23].

However, the viability of the bilateral network for the application it was originally intended for (unified two-port measurements of optical and optoelectronic devices) has not yet been established. Although the technique outlined in Reference 22 is elegant and conceptually simple, the effects of laser beat noise have not been accounted for. Moreover, the technique requires a pair of optoelectronic transmitters and receivers, which are expensive components. Hence attention has been turned to third generation instruments using optical equivalents of the test sets of microwave VNAs.

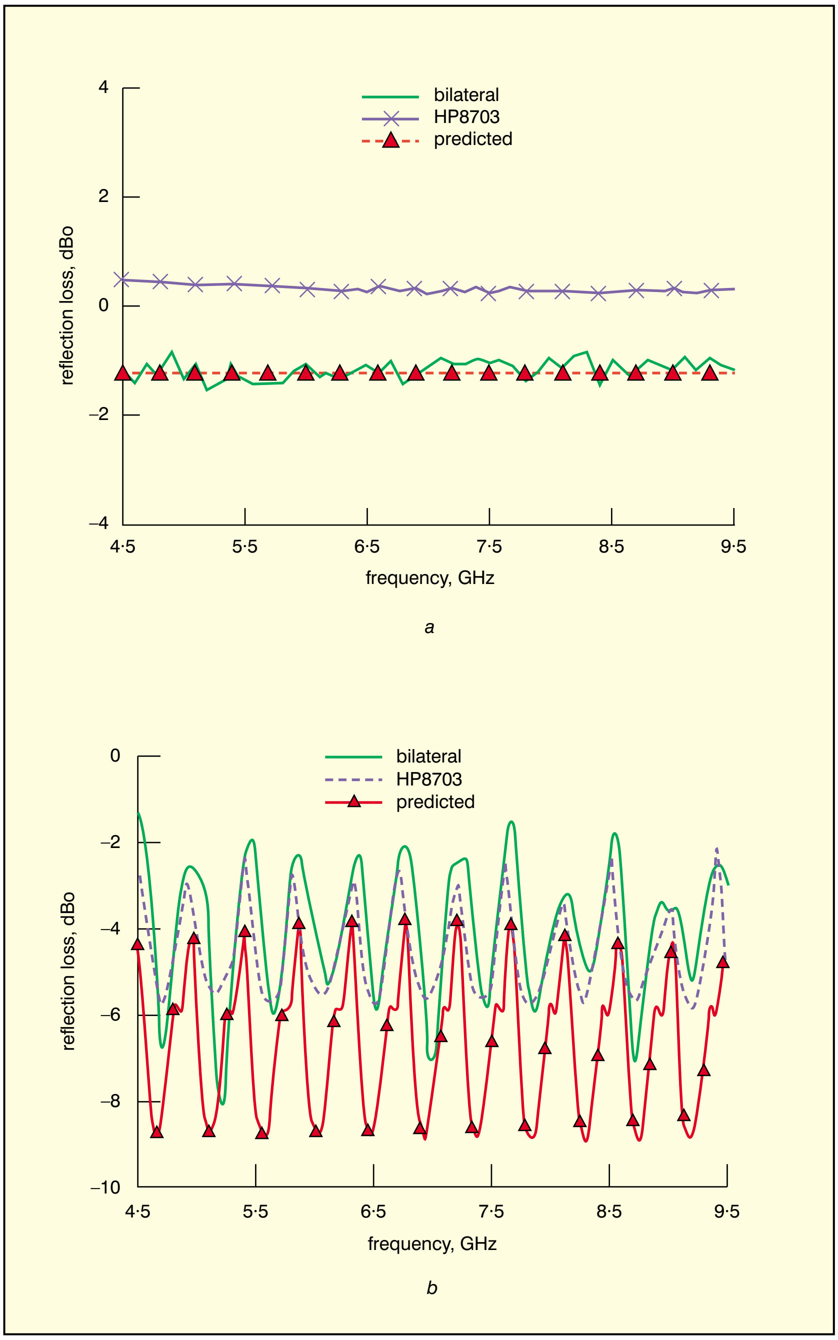


Fig. 9 De-embedded results of (*a*) mirror and (*b*) recirculating delay line (after Reference 23)

Two-port lightwave test set

A disadvantage of the BEON is its restricted modulation bandwidth, which is due to the use of a microwave circulator. For many optoelectronic two-ports (such as laser diodes and photodiodes), full two-port characterisation is a luxury that can be dispensed with for many applications. As an example, while the modulation response ($S_{21}^{E/O}$) and input microwave reflection coefficient ($S_{11}^{E/O}$) are important parameters, the use of optical isolators and the unilateral nature of the device mean that the reverse response and optical reflection coefficient are rarely of interest. In contrast, full two-port optical characterisation of optical components (such as optical amplifiers and isolators) is important. In the case of isolators, one requires a high value of isolation ($|S_{12}^{O/O}| \approx 0$), a low insertion loss ($|S_{21}^{O/O}| \approx 1$) and low input and output reflection coefficients ($|S_{11,22}^{O/O}| \approx 0$). Hence there exists a need to develop a two-port optical test set and the attendant calibration techniques.

A rudimentary two-port optical test set requiring manual connect-disconnect cycles during calibration

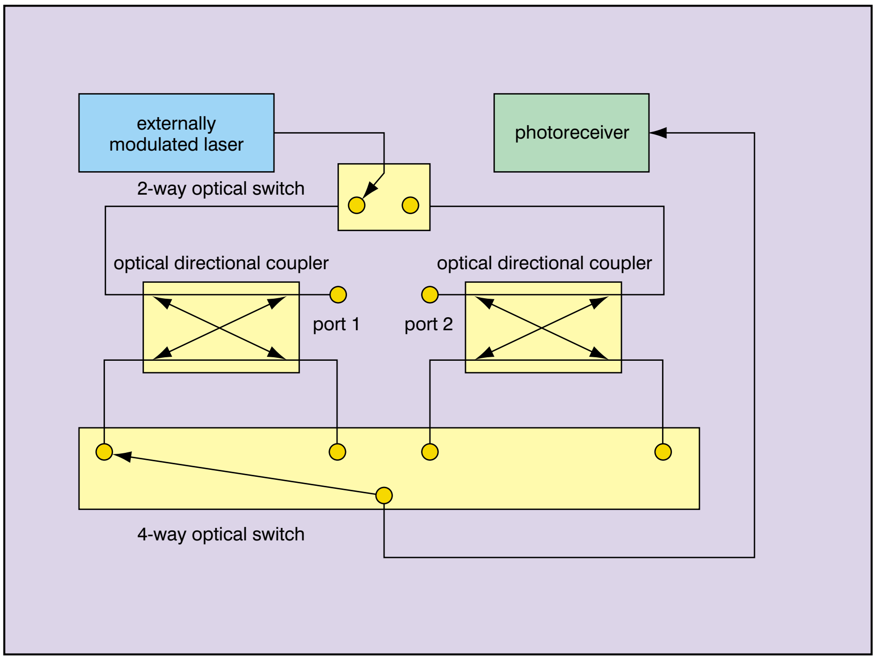


Fig. 10 A two-port optical test set

and measurement was reported by Quoc and Tedjini[24]. However, the lack of automation made this approach cumbersome and impractical, and also subject to connector repeatability errors. In addition, only a single calibration routine (TMR[25]—through-match-reflect) was investigated.

Recent work at Leeds has examined the use of an optical test set architecture similar to that of a microwave network analyser, using dual directional couplers and computer-controlled optical switches to direct modulated optical signals to the test ports and then separate the incident and reflected portions (Fig. 10). The resulting optical double reflectometer functions as a fully reversible transmission and reflection test set for optical two-ports and has a broad bandwidth. This has been used to examine the performance of all the T*xy* family of calibration techniques[16] in the optical domain with optical-fibre-based calibration standards[26]. An extensive experimental comparison between all the techniques has been carried out. It has been shown that techniques using optical attenuation (A) and match (M) standards provide the best broadband performance. Figs. 11 and 12 show typical results obtained. The calibrated results of the magnitudes of S_{11} of the dielectric-coated mirror at port 1, S_{11} of the Fresnel reflect at port 2, S_{21} of a recirculating delay line and S_{21} of a 20 dB attenuator are shown by way of example. For reflection measurements, the TAR and TAF calibration techniques give values very close to the nominal values of the DUTs.

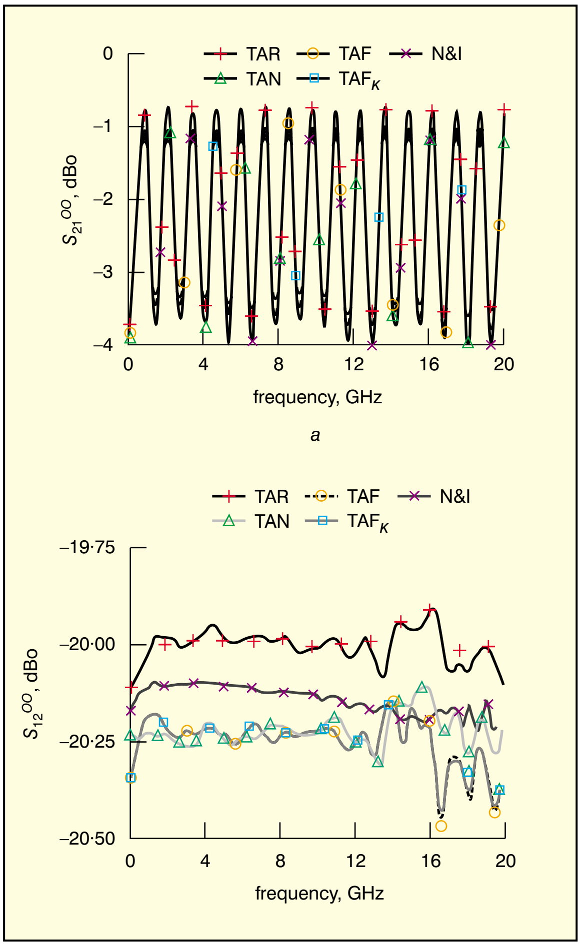


Fig. 11 T*ay*-calibrated optical transmission magnitude measurements: (*a*) $S_{21}^{o/o}$ of a recirculating delay line loop; (*b*) $S_{12}^{o/o}$ of a –20 dBo attenuator

Electro-optic network analyser

The two-port lightwave test set addresses the problem of error-corrected two-port O/O measurements without having the bandwidth restrictions of the modular approach using BEONs. However, it sacrifices the ability to perform E/O and O/E measurements. A two-port test set that can be used to provide error-corrected measurements of both E/O and O/E components has also been demonstrated at Leeds[27]. This approach allows these two types of components to

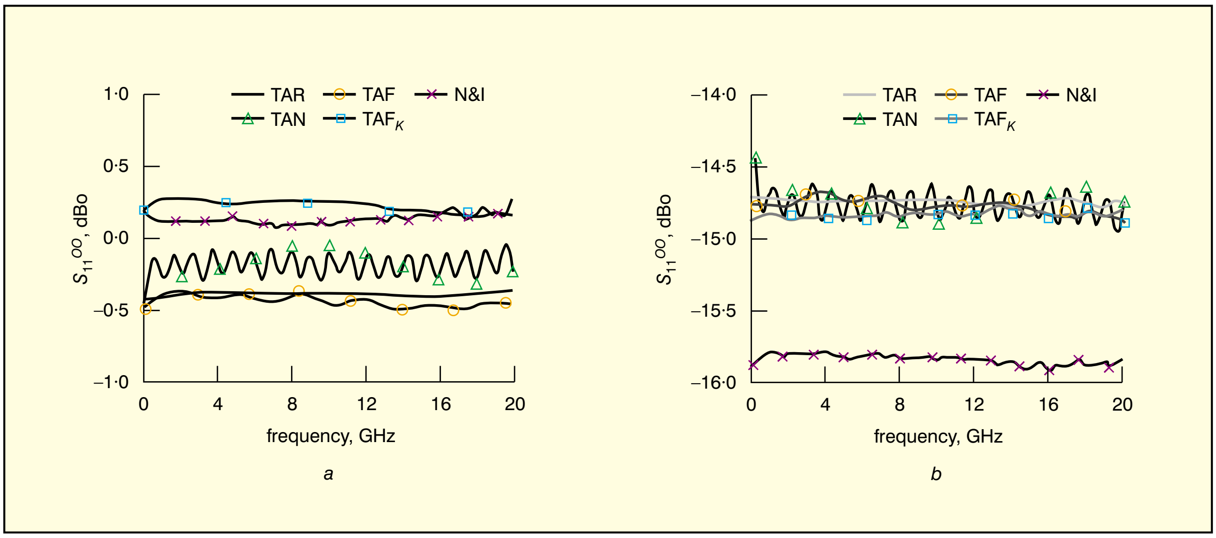


Fig. 12 Tay-calibrated optical reflection magnitude measurements: (a) $S_{11}^{o/o}$ of a 0·2 dBo reflect at Port 1; (b) $S_{11}^{o/o}$ of a Fresnel reflect at Port 2

be measured with a single test set; the calibration consists of two tiers and relies on the use of a BEON.

The E/O network analyser and its constituent test set is shown in Fig. 13. It consists of a pair of directional couplers, one microwave and the other optical, which are used to separate incident and reflected signals from the electrical and optical ports, respectively. In the case of the optical signals, these are photodetected and combined with those from the microwave coupler before being processed. The stimulus is applied from a microwave source, via a microwave switch to the two directional couplers. At the optical coupler, the microwave stimulus is first used to directly modulate a laser operating at 1·3 μm.

A major difficulty with measuring E/O and O/E components is that, unlike E/E and O/O two-ports, neither a through nor a reciprocal reflectionless standard exists. Hence the generalised T*xy* calibration procedure[16], which is widely used in microwave network analysis and has also been applied to O/O measurements, cannot be applied directly because the first standard is a through connection between the test ports. Electrical and optical test ports can only be connected together with an intermediate E/O or O/E component, for which it would be impossible to guarantee through-like behaviour.

This obstacle can be overcome with a two-tier calibration of the E/O network analyser. In the first tier, the microwave port (E_1) is transformed into an optical test port (O_1') with a BEON as shown in Fig. 14. This allows an optical version of the T*xy* calibration to be applied between ports O_1' and O_2, and at this stage the E/O network analyser can provide error-corrected measurements of O/O components between these ports. The T*xy* calibration procedure will see an effective error network at O_1' that is the cascade of error network A and the BEON. By treating the BEON as a black-box whose *S*-parameters are measured with an HP8703A lightwave component analyser, it is possible to remove its response from the composite error network during the second tier to obtain a normalised version of the error network A. Error network B can then be evaluated as detailed in Reference 16.

A prototype of the E/O network analyser has been implemented. The E/O and O/E measurements are carried out after calibrating the analyser with the two-

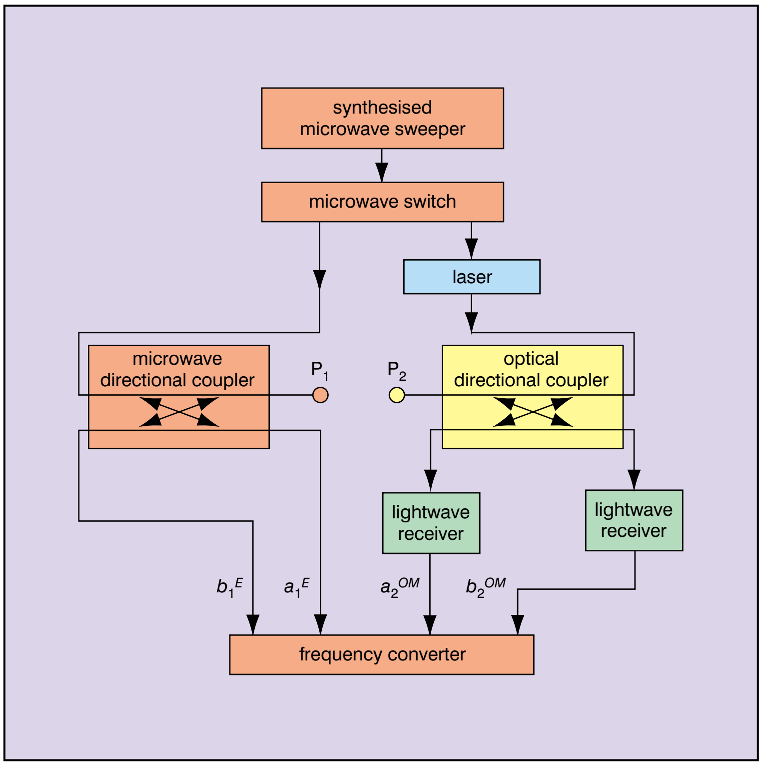


Fig. 13 An electro-optic network analyser

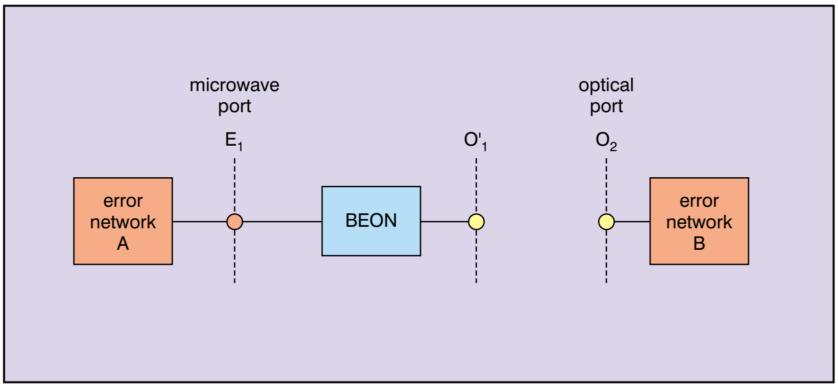


Fig. 14 Arrangement for calibration of the E/O network analyser

tier calibration. The calibration standards used in the first tier are an optical through (T), optical attenuator (A) and optical mirrors (R) cascaded in turn with the BEON at optical port 1 (O_1') and as stand-alone standards at optical port 2 (O_2). De-embedding of the BEON is then carried out to obtain the E/O and O/E calibration coefficients. This allows E/O and O/E two-port measurements to be conducted and compared with results obtained with the HP 8703A lightwave component analyser. Fig. 15 shows the measured forward transmission *S*-parameters of an Ortel 3541B laser diode transmitter and an HP 83411D amplified lightwave receiver. It is seen that the measurements with the HP 8703A and the E/O analyser follow each other closely over most of the frequency range.

Conclusions and discussion

Enormous strides have been made in microwave photonics in recent years. An example is the development of fibre radio systems using millimetre-wave modulation signals for the delivery of wireless services. These have been made possible through advances in optoelectronic and optical device technology and microwave photonic system integration. In this sense, the field has parallels with the microwave industry, where mass production of microwave monolithic integrated circuits has brought improved performance and reduced cost in applications such as wireless communications and satellite broadcasting. Key to this success were the enabling technologies of computer-aided design (CAD) and characterisation techniques, specifically network analysis.

The continued development of microwave and millimetre-wave photonics will also need to be supported by its own set of advanced CAD and characterisation tools. Lightwave network analysis not only plays a vital role in determining the small-signal performance of individual components in a microwave photonic system, but will also be an important tool in modelling these components. A good example is modelling of directly modulated laser diodes, in which parameter extraction techniques based on first generation lightwave network analysers have been used to obtain element values for equivalent circuits[10].

The drawbacks of first generation instruments are twofold: cumbersome and time-consuming measurement configurations, and calibrations that require the use of known standards. Both of these disadvantages have been overcome by the work at Leeds, which has demonstrated designs for second and third generation instruments. These remove the need for the DUT to be reversed in the test set. Moreover, the work has proved for the first time the feasibility of being able to apply self calibration techniques to the measurement of

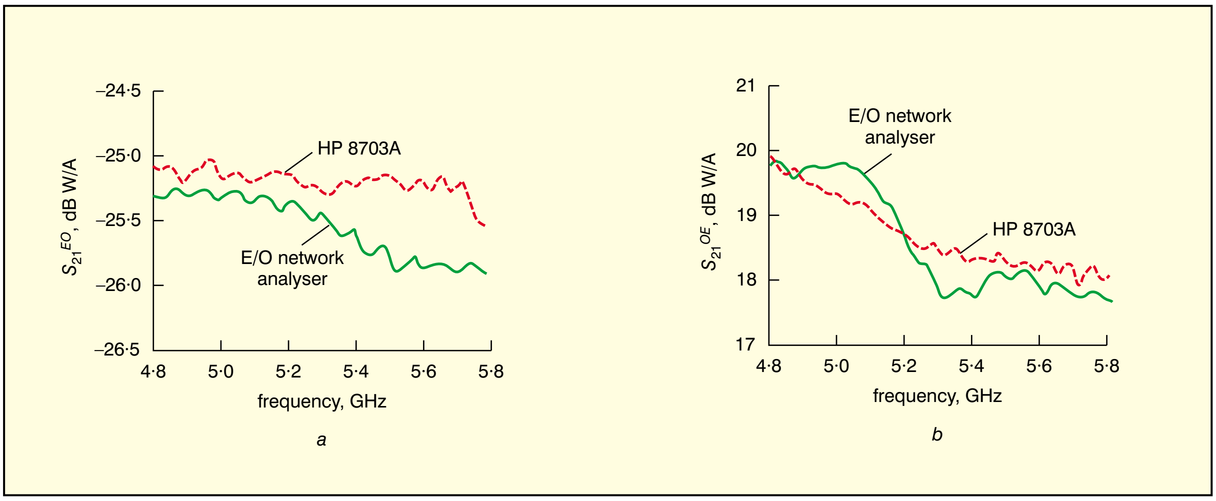


Fig. 15 Calibrated E/O and O/E measurements compared with those using an HP 8703A: (*a*) $S_{21}^{E/O}$ of Ortel 3541B laser diode transmitter; (*b*) $S_{21}^{O/E}$ of an HP 83411D amplified lightwave receiver

the microwave response of all types of lightwave component. With continued research and development, new opportunities will arise for lightwave network analysis measurements that are easier to carry out and more accurate than in the past.

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