0.82 μm, 260 μW wavelength laser beam which turns LD off. The circuit required 3.8 V and 1.5 mA, excluding the laser pre-bias of 19.5 mA, resulting in a power dissipation of 5.6 mW which was provided by the PV cell illuminated by a 0.82 μm wavelength laser diode. Light to the PV cell was coupled via a 55 μm core multimode optical fiber. The measured bandwidth of the circuit was 40 MHz at an optical input power of 150 μW, which gives an optical switching energy equal to 3.8 pJ. By improving the sensitivity of the HPT at low input powers [6], the switching energy can be reduced by approximately two orders of magnitude.

In conclusion, we have demonstrated an optically powered, multifunctional, integrated pixel for optical interconnections. Our results illustrate that optically powered smart pixels have the potential of being key components in future high density optical interconnection networks. A more detailed description of the pixel fabrication and performance, and how the several optical beams can be "managed" in a practical system implementation will be presented elsewhere.

## ACKNOWLEDGMENT

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# A Coherent Optical Network Analyzer

A. P. Freundorfer, *Member, IEEE*

***Abstract*—A novel measurement instrument is presented for evaluation of optical components similar to that of microwave network analyzer. This instrument is also capable of polarization measurements. Heterodyne mixing and small linewidth lasers with large tunable range make it a flexible tool for optical device evaluation and design. Experimental results are also presented.**

## INTRODUCTION

SUBMILLIMETER optical reflectometers [1], such as optical time-domain reflectometers OTDR [2]-[4], optical frequency domain reflectometers OFDR [5]-[7], and optical low coherence reflectometers OLCR [8] have been used either to evaluate optical components in the time domain or to derive spatial distance of the scattering centers. In optical communications, one is often interested in the frequency domain since future coherent optical communications systems will be frequency division multiplexed [9]. In such a system, it is of interest that amplitude and phase are linear as a function of optical frequency. Polarization is also of interest since some optical components use polarization conversion as a means of obtaining their goal.

The proposed instrument will be able to measure the scattering parameters of a two-port optical device under test (ODUT) for a given optical probe wave. The optical scattering parameters are vectors and this implies that polarization, phase, and magnitude detection are important. The ODUT here may be optical material, optical components, or fiber optical communication components.

## THEORY OF OPERATION

For simplicity, the polarization independent measurements will be discussed first, and then the theory of polarization measurements will be add. The object of network analysis is to measure the scattering parameters of a two-port optical device. Scattering parameters or $s$ parameters are reflection and transmission coefficients of ODUT.

Let $a$ be an optical wave traveling into a port (sometimes called a probing wave) and let $b$ be the optical wave travelling away from a port (often called a reflected or scattered wave). Referring to this convention along with Fig. 1, the $s$ parameters will be explained.

Fig. 1 shows the relationship between the $s$ parameters and the probing and scattered waves. For example, a probing

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The author is with the Department of Electrical Engineering, Queen's University, Kingston, Ont., Canada K7L 3N6.

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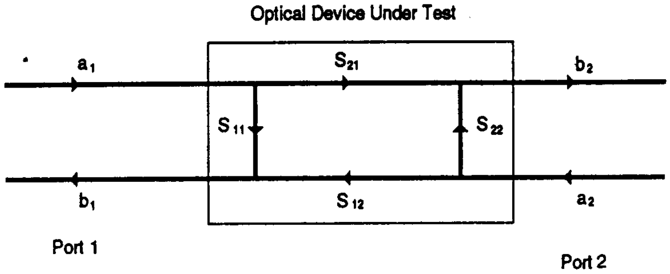

Fig. 1. Signal flow graph of optical device under test.

wave $a_1$, which is partially reflected at port 1, becomes $s_{11}$. The rest of the signal, which is transmitted through the device and exits port 2, becomes $s_{21}$. Similarly, the fraction of $a_2$ that is reflected from port 2 becomes $s_{22}$ and the fraction transmitted from port 1 is $s_{12}$. Thus, the outputs can be related to the inputs by the equation

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = [s] \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (1)$$

where $[s]$ is the scattering matrix.

In general, the $s$ parameters have phase and magnitude. Thus, heterodyne mixing is used to preserve the phase information at the receiver. This can be further quadrature-detected to obtain phase and magnitude information.

Two-port scattering parameters are easy to measure at high frequencies because the ODUT can be easily terminated by an absorber in the measuring system. This allows for broadband swept frequency measurement which is stable over a large frequency range.

## POLARIZATION

As mentioned earlier, optical systems sometimes use polarization conversion as a method of operation. Thus, one is interested in the polarization effects of ODUT on the probing wave. To measure these effects, it is necessary to control the polarization of the probing wave. This results in the elements of the scattering matrix $[s]$ becoming a matrix rather than a single value. For example, $s_{11}$ becomes

$$\begin{bmatrix} b_{1x} \\ b_{1y} \end{bmatrix} = \begin{bmatrix} s_{11xx} & s_{11xy} \\ s_{11yx} & s_{11yy} \end{bmatrix} \begin{bmatrix} a_{1x} \\ a_{1y} \end{bmatrix} \quad (2)$$

where the subscript $x$ and $y$ refer to the polarization of the probing and scattered waves. Here $x$ and $y$ are orthogonal linear polarizations. The polarization matrix, (2), can be obtained by setting $a_{1x} = 1$ and $a_{1y} = 0$, i.e., sending only $x$ polarization, and measuring $b_{1x} = s_{11xx}$ and $b_{1y} = s_{11yx}$. Likewise one can obtain $s_{11xy}$ and $s_{11yy}$ by setting $a_{1x} = 0$ and $a_{1y} = 1$.

## EXPERIMENTAL SETUP

To measure the optical scattered wave of ODUT, the novel circuit is given in Fig. 2.

$S_1$, $S_2$, $S_3$, and $S_4$ are shutters that may be switched on according to the scattering parameters to be measured.

For example, if one measures $s_{11}$, shutter $S_3$ is closed while $S_1, S_2$, $S_4$ are open. One sees that the optical circuit in Fig. 2 is reduced to a variant of a Michelson interferometer, similar in structure to [5], with the optical wave in the reference arm frequency shifted by the acoustic optical modulator (AOM). $a_2 = 0$ since the shutter $S_3$ is closed, thereby eliminating the $s_{12}$ factor in $b_1$ of (1). The reference arm wave is then optically heterodyned with the scattered wave $b_1$ of ODUT at receiver 1. In the mixing process, the phase is preserved. All one has to do to get $\mathrm{Re}\{b_1\}$, inphase, and $\mathrm{Im}\{b_1\}$, quadrature phase, for a given $a_1$ is to use a quadrature detector with the local oscillator (LO) as the REF signal that feeds the AOM. $a_1$, is obtained in the same way that $b_1$ is obtained, except that ODUT is replaced by a reference mirror which results in $s_{11} = -1$ and thus $b_1 = -a_1$. Since both $b_1$ and $a_1$ are measured, one can obtain $s_{11} = b_1/a_1$. The source can then be frequency-swept by changing the injection current, piezo voltage or temperature of the laser [10] in order to obtain $s_{11}$ as a function of optical frequency.

If one measures $s_{21}$, shutter $S_1$ is closed while $S_2$, $S_3$, $S_4$ are open. One sees that the circuit in Fig. 2 is reduced to a Mach-Zehnder interferometer. $a_2 = 0$ because shutter $S_2$ is closed so that $s_{22}$ term is eliminated from $b_2$ in (1). The reference arm is modulated by the AOM at the intermediate frequency of $f_{if}$ at the REF input. This is then optically heterodyned with the scattered wave $b_2$ to produce an intermediate frequency at the output of receiver 2. Next it is quadrature-detected to obtain $\mathrm{Re}\{b_2\}$ and $\mathrm{Im}\{b_2\}$ for a given $a_1$ by using the input signal to the AOM as the LO. The probing wave $a_1$ is obtained in the same way that $b_2$ is obtained except that ODUT is removed. This results in $s_{21} = 1$ and thus $b_2 = a_1$. Both probing and scattered waves are detected and the appropriate scattering parameter, $s_{21} = b_2/a_2$, is measured. The frequency can be swept to obtain $s_{21}$ versus optical frequency.

The measurements of $s_{22}$ and $s_{12}$ are done in a similar fashion as $s_{11}$ and $s_{21}$.

## POLARIZATION MEASUREMENTS

Receivers 1 and 2 can be replaced by the receiver in Fig. 3 so as to be able to detect the $x$ and $y$ components of the polarization.

The source has a half-wave plate, $P_1$, in front of it so as to control the polarization of the probing beam. By rotating $P_1$, one can obtain any linear polarization. The polarization controller $P_2$, a half-wave plate, tracks $P_1$ so as to keep the polarization at 45° with respect to the polarized beam split-

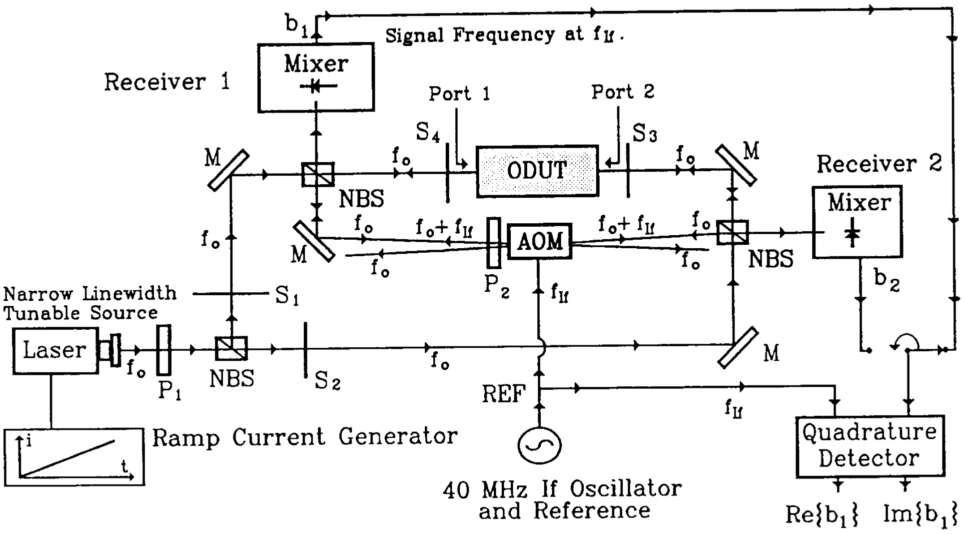

Fig. 2. Coherent optical network analyzer.

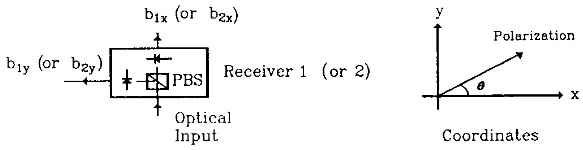

Fig. 3. Polarization sensitive receiver.

ters (PBS) in the receiver shown in Fig. 3. Thus, the optical LO power to both polarizations $x$ and $y$ is equally divided at receivers 1 and 2. The LO mixes with the $x$ and $y$ scattered waves of ODUT to produce the appropriate intermediate frequency output at the receivers. Therefore, the polarization scattering matrix, as, for example, (2), can be determined by first transmitting the x polarization then the $y$ polarization. A general elliptical polarization of the scattered wave can be easily determined when the polarization and phase information are given.

## Experimental Results

Using a Nd-YAG laser at 1.319 $\mu$m and output of 25 mW with a tuning range of 18.3 GHz, the coherent optical network analyser in Fig. 2 was constructed. The coherence length of the laser was approximately 25 km [5]. Thus, the scattered wave from ODUT will be coherently detected [5]. The ODUT in Fig. 4 was a 0.512 in optically flat glass with an incident beam perpendicular to the parallel surfaces. Since the response of this ODUT was polarization independent, it was not necessary to use a polarization detector. Also ODUT was a reciprocal device on $s_{12}$ and $s_{22}$ are necessarily displayed. Fig. 5 shows some measured polarization profiles of the quarter and half-wave plates which were used when the receiver in Fig. 2 was replaced by that in Fig. 3. Four polarization plots are given covering 18.4 GHz bandwidth for each example. The dynamic range of the system was measured to be about 60 dB.

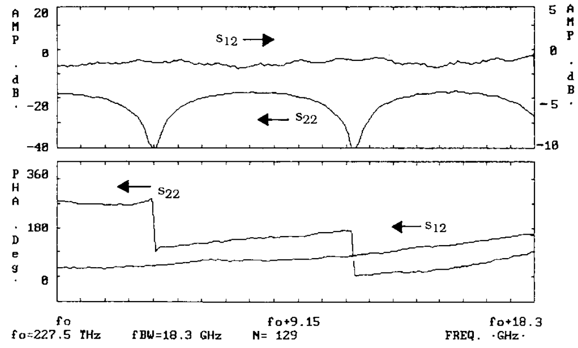

Fig. 4. The measured scattered parameters $s_{21}$ and $s_{22}$ of a 0.512 in thick optically flat glass. Note the interference of the waves from the front and back surfaces in $s_{22}$.

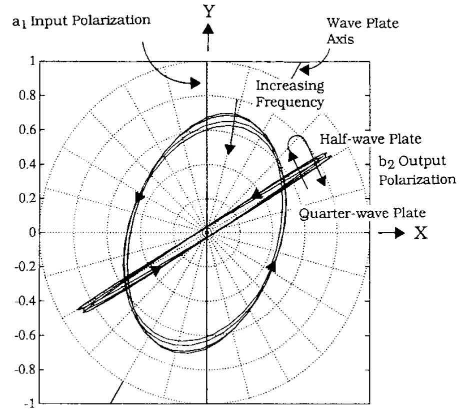

Fig. 5. Measured polarization characteristics of a quarter and a half wave plates at −30° from vertical. The input beam was a vertical linear polarization.

## CONCLUSION

It is possible to have a novel coherent optical network analyzer similar to that of the microwave network analyzer. This optical network analyzer will be able to extract polarization information as well as the usual phase and magnitude information. The resultant instrument will assist in the design of optical components.

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# Cross-Phase Modulation Influence on a Two-Channel Optical PSK Homodyne Transmission System

Seiji Norimatsu and Katsushi Iwashita

*Abstract*—**The residual amplitude modulation of adjacent channels causes cross-phase modulation which is responsible for degradation in the error rate performance of a phase detection system. This influence on a two-channel 10 Gb/s optical PSK homodyne transmission system is experimentally evaluated. A penalty is observed for more than 6 dBm fiber input power with 28% residual amplitude modulation passing through a 100 km dispersion shifted-fiber.**

## INTRODUCTION

OPTICAL PSK homodyne detection offers the best sensitivity of any binary signalling technique and requires only the same electrical bandwidth as the bit rate. Therefore, it is suitable for multigigabit long distance transmission systems [1]. Moreover, it can reduce the channel spacing more than heterodyne detection systems in optical frequency division multiplexing (FDM) systems. There are several candidates for phase modulators such as $LiNbO_3$ and semiconductor modulators. However, these phase modulators induce residual amplitude modulation more or less. This modulation degrades transmission performance, especially in optical FDM systems, due to cross-phase modulation [2]-[4]. This degradation is caused by the nonlinear phase change induced by amplitude modulation.

This letter reports the measured cross-phase modulation influence on a two-channel optical PSK homodyne detection system due to residual amplitude modulation using dispersion shifted fiber.

## EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The transmitter (TR1) and the local oscillator are 1.5525 $\mu$m wavelength DFB LD's with external cavities. The adjacent channel transmitter (TR2) is a 1.55357 $\mu$m wavelength DFB LD without an external cavity. The channel spacing is 134 GHz. The optical powers of TR1 and TR2 are set equal by attenuators, ATT 1 and ATT 2, respectively. Fiber-pigtailed traveling-wave electrode Ti:$LiNbO_3$ optical phase modulators are used to produce 10 Gb/s PSK signals. The two signals for the transmitters are combined after making the same polarization

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The authors are with NTT Transmission Systems Laboratories, Kanagawa 238-03, Japan.

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