Extracting S-parameters of bilateral electro-optic network for lightwave component analyzer calibration

D Frolov, A Levchenko, K Korotkov

Kuban State University, 149 Stavropolskaya st., Krasnodar, Russia

E-mail: frolov.drf@gmail.com

Abstract. A new method for extracting E/O and O/E S-parameters of a bilateral electro-optic network (BEON) is theoretically proposed. It is based on measuring reflection coefficients from three optical loads: an absorber and two mirrors. This technique includes two series of reflections measurements: first when loads are connected to optical port of BEON directly and second when loads are connected in series with optical waveguide of fixed length. Using two BEONs and this calibration technique allows to make calibrated lightwave measurements with a standard microwave network analyzer without using additional electro-optical equipment such as lightwave component analyzer or optical heterodyne techniques.

1. Introduction

A bilateral electro-optic network (BEON) and its use for lightwave network analysis measurements was first reported by Pollard [1]. Unlike majority E/O and O/E components that are not reciprocal in nature BEON is a network in which forward (electrical to optical) and reverse (optical to electrical) transmission is allowed. Using BEONs in lightwave network analyzers instead of single laser diodes and photodetectors allow to use an optical analogue of various microwave two-port calibrations such as TRL. This allows to measure full S-matrix of O/O components. However it sacrifices the ability to perform E/O and O/E measurements.

A two-tier calibration of the electro-optic analyzer was also reported by Pollard [2]. However in this calibration BEON is treated as a blackbox whose S-parameters are measured with a HP8703A or other lightwave component analyzer, that uses the optical heterodyne technique [3] to measure the frequency response $S_{21}^{O/E}$ of its photodetector. This technique uses two Nd:YAG lasers, one passing through the modulator, the other functioning as a local oscillator to convert one of the sidebands of the modulated carrier to IF frequency. This IF frequency can be swept by sweeping the wavelength of laser beam, thus the wavelength can be controlled by varying the temperature of YAG crystal.

However these measurements are conducted with complex optoelectronic system that includes lasers, spectrum analyzer, temperature control system, different lenses and polarization control devices. This can be a serious disadvantage in case if one needs to characterize an unknown photodetector or a BEON that is operated in O/E mode because it is impossible to make such measurements with a standard lightwave component analyzer like HP8703A.

2. Description of measurement procedure

Due to the fact that BEON has low bandwidth because it contains circulator [1], for calibration we need some optical devices that will be equivalent to electrical loads: open, short, matched load, and the optical equivalent of airline. It will be shown that in the proposed method it is needed to know exactly only parameters of short equivalent optical load (mirror) that is not hard to calculate for specific optical connector and fabrication of such mirror for a fixed optical wavelength has no difficulties. An equivalent of matched load – an optical absorber can also be easily done.

The optical equivalent of airline for this calibration should be long enough to fit necessary number of points in frequency domain. A piece of optical fiber can be used and due to the small value of loss in it (0.3 dB/km, at 1310 nm wavelength) comparing to RF lines (1.6 dB/m) this optical fiber can be ten times longer than ordinary coaxial RF line. Exactly this condition allows to do this calibration at narrow bandwidth and it is possible to adjust this bandwidth for specific BEON by changing the length of optical fiber (waveguide).

Unfortunately, it is rather difficult to fabricate an equivalent open optical load that will provide 180° RF phase difference between forward and reflected optical waves that are modulated with RF signal (in the optical fiber). But accordingly to low bandwidth of calibration it is possible to fabricate this load as a quarter RF wave optical waveguide with a mirror on the end. The quarter RF wave optical waveguide should be calculated for the average RF frequency of the calibration bandwidth for specific BEON.

The process of extracting scattering parameters of BEON can be done with a standard VNA. First it is needed to calibrate vector network analyzer (VNA) with one of known techniques [4,5,6]. After calibration, BEON electrical port should be connected to one of VNA's ports and six S11 measurements with optical loads should be done as it is shown in figures 1 and 2.

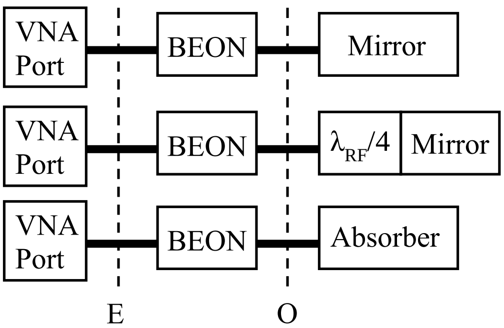

Figure 1. VNA measures complex reflection coefficients of BEON's electrical port with three type of loads: first mirror (equivalent to short load at RF), second mirror placed $\lambda_{RF}/4$ far (open load) and absorber (matched load at RF).

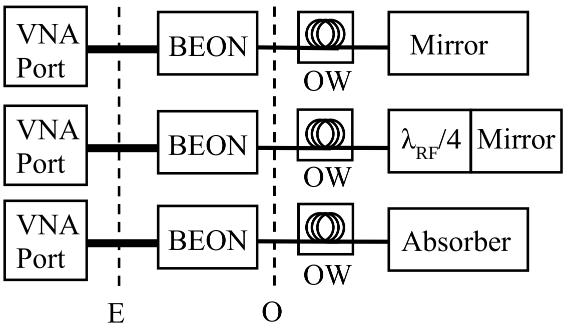

Figure 2. VNA measures complex reflection coefficients of BEON's electrical port with the same loads, but connected in series with optical waveguide (OW) of calibrated length (equivalent to air line at RF).

As a result we have six complex reflection coefficients that can be presented as a system of six equations – three equations (1-3) for reflections without optical waveguide and three with it (4-6):

$$S_S = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_S}{1 - S_{22}^{O/O} \Gamma_S} \tag{1}$$

$$S_O = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_O}{1 - S_{22}^{O/O} \Gamma_O} \tag{2}$$

$$S_L = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_L}{1 - S_{22}^{O/O} \Gamma_L} \tag{3}$$

$$S_S^{/} = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_S^{/}}{1 - S_{22}^{O/O} \Gamma_S^{/}} \tag{4}$$

$$S_O^{/} = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_O^{/}}{1 - S_{22}^{O/O} \Gamma_O^{/}} \tag{5}$$

$$S_L^{/} = S_{11}^{E/E} + \frac{S_{21}^{E/O} S_{12}^{O/E} \Gamma_L^{/}}{1 - S_{22}^{O/O} \Gamma_L^{/}} \tag{6}$$

Using analogue with (1-6) for $\Gamma_S^{/}$, $\Gamma_O^{/}$, $\Gamma_L^{/}$ we also have three equations:

$$\Gamma_S^{/} = S_{11}^{OW} + \frac{S_{21}^{OW} S_{12}^{OW} \Gamma_S}{1 - S_{22}^{OW} \Gamma_S} \tag{7}$$

$$\Gamma_O^{/} = S_{11}^{OW} + \frac{S_{21}^{OW} S_{12}^{OW} \Gamma_O}{1 - S_{22}^{OW} \Gamma_O} \tag{8}$$

$$\Gamma_L^{/} = S_{11}^{OW} + \frac{S_{21}^{OW} S_{12}^{OW} \Gamma_L}{1 - S_{22}^{OW} \Gamma_L} \tag{9}$$

where S_{11}^{OW}, S_{12}^{OW}, S_{21}^{OW} and S_{22}^{OW} are S-parameters of optical waveguide.

Values S_S, S_O, S_L, $S_S^{/}$, $S_O^{/}$, $S_L^{/}$ are known from the measurements, all other values: $S_{11}^{E/E}$, $S_{21}^{E/O} S_{12}^{O/E}$, $S_{22}^{O/O}$, Γ_O, Γ_L, S_{11}^{OW}, $S_{21}^{OW} S_{12}^{OW}$, S_{22}^{OW} are unknown. So we have system with six equations and eight unknown values. By solving analytically system of equations in fixed frequency points where S_{11}^{OW} and S_{22}^{OW} parameters compensate each other and their influence will be very small, because in these fixed frequency points the equivalent RF length of optical waveguide will provide 180° difference between RF waves reflected from the ends of the optical waveguide, we shall find twelve solutions. Using the condition that reflection from open equivalent load has limits $0.5 \le |\Gamma_O| \le 1$ and reflection from matched equivalent load (absorber) has limits $0 \le |\Gamma_L| \le 1$ we can leave only two solutions. In the first, the phase of open load will increase with frequency increasing and in the second – the phase will decrease. Accordingly to the physical meaning, we can leave only one solution. Wherein because of the high length of the optical waveguide in narrow bandwidth it is possible to get many points with known derivatives that makes possible to use Hermite polynomials to get values of Γ_O, Γ_L, and by substituting them to (1-3) we can extract $S_{11}^{E/E}$, $S_{21}^{E/O} S_{12}^{O/E}$, $S_{22}^{O/O}$ parameters of BEON under test.

3. Conclusion

Theoretically is proposed a simple principle for extracting full S-matrix of a BEON both in E/O and O/E directions that is based on using only one port of standard microwave VNA three optical loads and a light waveguide of fixed length. The benefits of this calibration process are:

1) It is not needed fabricate several precision optical load standards and measure their parameters. Only one load (mirror) is needed to be precisely characterized.
2) It is possible to calculate inaccuracy of calibration and it is not needed to calibrate optical ports of BEON with some other lightwave component analyzer.
3) Using the proposed calibration technique it is possible to make lightwave components measurements by using only an ordinary VNA and a pair of BEONs.

References

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