A Generalized Approach to Optical Low-Coherence Reflectometry Including Spectral Filtering Effects

Uwe Wiedmann, Philippe Gallion, *Senior Member, IEEE, Member, OSA,* and Guang-Hua Duan, *Member, IEEE*

***Abstract*— In the interpretation of optical low-coherence reflectometry measurements, the reflectivity of the device under test is in general supposed to be with a slow dependency on optical wavelength. However, recent research aims at investigating strongly wavelength-dependent devices, such as fiber Bragg gratings and semiconductor lasers. In this paper, a general theory including spectral filtering effects is developed. It appears as a generalization of previously reported results only valid under special conditions.**

***Index Terms*— Low-coherence reflectometry, optical interferometry, spectral filtering.**

I. INTRODUCTION

OPTICAL low-coherence reflectometry (OLCR) was developed about ten years ago [1], and it is now a well-established tool for detecting, localizing, and quantifying reflecting discontinuities and irregularities in optical waveguides and circuits. For many applications, the reflectivity of the device under test (DUT) can be considered wavelength-independent in the spectral range of the broadband light source. There are however many applications in which spectral filtering of the light source by the DUT must be taken into account. These include among others the analysis of fiber Bragg gratings [2], [3] and distributed feedback lasers. Another application is the determination of gain as a function of wavelength and position in semiconductor laser diodes [4].

Interpretation of the measured reflectogram also becomes difficult when there are several possible paths for the test light. Reflections occurring in independent light paths are often indistinguishable from several reflections in one single path. In other cases, one single discontinuity can show up twice in the reflectogram due to different optical light paths. In this paper, we first develop a general theory of optical low-coherence reflectometry including spectral filtering effects in the DUT. We then show how other approaches found in literature can be derived from this theory, and finally show how it can be applied to the multiple path problem.

II. THEORY

Let us consider the OLCR setup in its basic form, which is a scanning Michelson interferometer with the device under test (DUT) placed in one of its arms (Fig. 1). A spatially resolved reflectogram is obtained by varying the optical path length of the other arm. An intuitive explanation of its principle is that interferences only occur when the lengths of both arms are the same to within a coherence length of the light source. Reflections from within the DUT can thus be resolved when their spatial separation is larger than the coherence length of the probe light. This simplified explanation is however only accurate when the source spectrum is not altered by wavelength-dependent effects inside the DUT. The following theory will describe the general case taking into account any possible filtering effects.

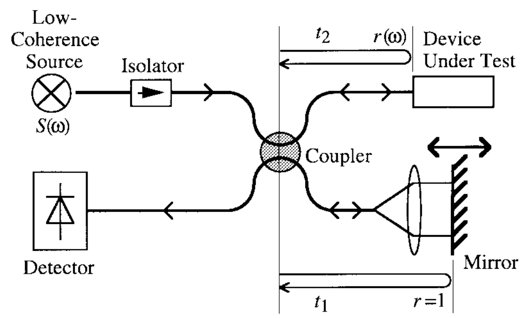

Fig. 1. Simplified schematic diagram of the optical low-coherence reflectometer.

The amplitude of the photoelectric field emitted by the source can be written in the general case as [5], [6]

$$E(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \sqrt{S(\omega)}\, e^{j(\omega t + \varphi(\omega))}\, d\omega$$

where $S(\omega)$ is its power spectral density, and $\varphi(\omega)$ is a frequency-dependent phase. We suppose that the phases for different frequencies are not correlated, which means that

$$\left\langle e^{j(\varphi(\omega)-\varphi(\omega'))} \right\rangle = \delta(\omega - \omega')$$

where the angle brackets indicate the time average, and δ denotes the Dirac distribution. In the reference arm, the light is reflected by a wavelength-independent mirror with a variable time delay t_1. After two passes through the 3-dB coupler, the field $E_1(t)$ reflected by the reference arm is thus

$$E_1(t) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} \sqrt{S(\omega)}\, e^{j(\omega[t-t_1]+\varphi(\omega))}\, d\omega.$$

Any DUT can be entirely described by a frequency-dependent reflectivity $r(\omega)$ and, for convenience, an additional time delay t_2, which is equal to the time the light takes for a return trip to and from the point for which the reflectivity $r(\omega)$ of the DUT has been specified. The field $E_2(t)$ reflected

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by the DUT is thus

$$E_2(t) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} \sqrt{S(\omega)}\, r(\omega)\, e^{j(\omega[t-t_2]+\varphi(\omega))}\, d\omega.$$

The intensity detected by the photodiode is then

$$I(\tau) \propto \Big\langle (E_1(t) + E_2(t))^*(E_1(t) + E_2(t)) \Big\rangle.$$

The terms $E_1(t)^*E_1(t)$ and $E_2(t)^*E_2(t)$, independent of the time difference $\tau = t_2 - t_1$ between the two interferometer arms, only constitute a constant offset and will be neglected in the following treatment. They do however contribute to the noise level [7], a topic which is beyond the scope of this paper. The remaining cross products, depending on τ, are

$$I(\tau) \propto 2\langle \Re\{E_1(t)^* E_2(t)\}\rangle$$

where $\Re$ denotes the real part. This leads to

$$I(\tau) \propto \frac{1}{4\pi} \Re\bigg\{ \int_{-\infty}^{+\infty} S(\omega)\, r(\omega)\, e^{j\omega\tau}\, d\omega \bigg\}$$

where the double integration has been reduced to a single one due to the frequency δ-correlation. The reflectometric signature of any given device as a function of distance $x = c\tau$ where c is the velocity of light in vacuum, can thus be calculated from the source spectrum $S(\omega)$ and the reflectivity $r(\omega)$ of this device in the frequency domain. As no information is lost by taking only the real part, this type of low-coherence reflectometry is called phase-sensitive OLCR or complex OLCR [8], [9]. The corresponding measurement setup requires very careful control of the path difference between the interferometer arms, which is in general done by adding a reference laser to the setup. For many applications, however, the phase information is of minor interest. This means that only the magnitude without phase information needs to be detected, thus

$$I_{\text{mag}}(\tau) \propto \frac{1}{4\pi} \bigg| \int_{-\infty}^{+\infty} S(\omega) r(\omega)\, e^{j\omega\tau}\, d\omega \bigg|.$$

The measurement setup necessary for detecting only the magnitude is considerably simpler than that for complex OLCR, which is why this type of OLCR is often chosen for commercially available devices. It is in particular possible to use a continuously moving scanning mirror and to detect at the Doppler shift frequency, which results in eased electrical detection and a short measurement time. The detection of the magnitude only does however strongly restrict the mathematical treatment possible with the measured data. We define the measured reflectivity as being proportional to the detected photocurrents, in the way that

$$r_{\text{meas}}(\tau) = \Re\bigg\{ \int_{-\infty}^{+\infty} S(\omega)\, r(\omega)\, e^{j\omega\tau}\, d\omega \bigg\}$$

for the complex reflectivity and

$$r_{\text{meas, mag}}(\tau) = \bigg| \int_{-\infty}^{+\infty} S(\omega) r(\omega)\, e^{j\omega\tau}\, d\omega \bigg|$$

for the reflectivity in the case where only the magnitude of the backreflection is detected. It can be seen that the measured reflectivity is essentially the Fourier transform of the frequency-dependent reflectivity $r(\omega)$ of the DUT. The calculation from $r(\omega)$ to the measured reflectivity can thus be implemented easily on a computer by using a fast-Fourier transform (FFT).

III. Some Particular Solutions

A. Wavelength-Independent Backreflection, Low Backreflection Level, and No Absorption

Suppose the DUT does not contain regions absorbing or amplifying the injected test light. In the case of wavelength-independent backreflection and low backreflection values, the optical field propagating in the DUT can then be supposed to be of constant amplitude along the entire DUT. Suppose the reflectivity of the DUT as a function of the optical path length x_{opt} is given by $r(x_{opt})$. If the group index of the DUT is constant, the reflectivity of the device as a function of position x is given by $r(x_{opt}) = r(n_g x)$, where n_g is the group index of the device. The reflectivity as a function of the delay τ is then equal to $r(\tau) = r(x_{opt}/c)$ where c is the velocity of light in vacuum. In this case the reflectivity of the DUT in the time domain $r(\tau)$ is equal to the Fourier transform of its reflectivity in the optical frequency domain $r(\omega)$

$$r(\tau) = F\{r(\omega)\}_\tau.$$

In the case of an ideal white source, the reflectivity $r_{\text{meas, mag}}(\tau)$ measured by the OLCR is equal to the reflectivity $r(\tau)$ of the DUT. For a source having the frequency-dependent spectral density $S(\omega)$, the measured reflectivity in the time domain becomes

$$r_{\text{meas, mag}}(\tau) = r(\tau) * F\{S(\omega)\}_\tau$$

where $F\{S(\omega)\}$ is equal to the autocorrelation function of the light source, and "$*$" denotes the convolution. The measured reflectivity in the space domain is then given by $r_{\text{meas, mag}}(x_{opt}) = c r_{\text{meas, mag}}(\tau)$. It must be stressed that x_{opt} is not the physical but the optical path length in the DUT. In cases where the DUT is composed of several elements of different refractive group indexes, either the length or the refractive group index of these elements can be calculated from the other one of these parameters.

B. Wavelength-Independent Backreflection and Absorption

Using the same technique as in the case of low backreflection level, an equivalent reflectivity $r_{eq}(\tau)$ in the time domain can be calculated by

$$r_{eq}(\tau) = F\{r_{eq}(\omega)\}_\tau.$$

The equivalent backreflection level $r_{eq}(\tau)$ does however not correspond directly to the real backreflection level $r(\tau)$ of the DUT. The correspondence can be made by taking into account a transmission factor $T(\tau)$ [10]. It must be noted that the value of $T(\tau)$ is a function of the position of the backreflection, and this function is not known in the general case. There exist however cases in which the determination of $T(\tau)$ from the measured reflectogram can yield interesting information about the DUT. This is for example the case for multiple round-trip reflections from the front and back end facets of a waveguide segment as the level difference between two successive facet reflections corresponds directly to the round trip loss of the waveguide segment. This information can be interesting in the analysis of passive devices, but also for active devices, such as semiconductor lasers.

C. Dispersive Material and Localized Reflections

In a dispersive material, the reflectometric signature of a single reflection broadens as a function of position in the dispersive material, and simultaneously its amplitude decreases. The maximum value of its envelope is thus not directly proportional to the reflectivity value. However, the reflectivity value is proportional to the integral of the absolute value of the reflectometric signature [11], and its value can thus be determined from

$$r(\tau) = \int_{\tau_1}^{\tau_2} r_{\text{meas, mag}}(\tau)\, d\tau$$

where τ_1 and τ_2 delimit the OLCR signature of the broadened single peak. It must be noted that in this case there is no need for the OLCR setup to be phase-sensitive. One application of the above formula is for the determination of the round-trip loss of semiconductor waveguides, which are often strongly dispersive.

D. Dispersive Material and Overlapping Signatures

If the OLCR setup is phase-sensitive, it is possible to calculate the reflectogram one would have obtained when the DUT was nondispersive [9]. This is done by a wavenumber scale transformation of the measured reflectogram data using the dispersion parameters of the DUT, which must have been previously determined. In the same formalism, a rugged source spectrum can also be accounted for. The calculated reflectogram is what one would have obtained with a nondispersive DUT and an ideal source spectrum. The resolution of this calculated reflectogram is not any more affected by dispersion effects in the DUT, so that for example the round-trip loss of an optical waveguide can directly be determined from the height difference between the multiple facet reflection peaks in the reflectogram.

E. Lossless Bragg Grating

This point mainly refers to fiber Bragg gratings, which can in general be considered to be lossless. Other applications could include DFB lasers near threshold, i.e., at the operating point where the amplification is roughly equal to the absorption in the waveguide. It can be shown that for lossless Bragg gratings, the modulus of the coupling coefficient $|\kappa(x)|$ of the grating can be determined from the OLCR signature. Let the mean group index of the device be constant over the length of the grating and equal to n_g. Using the coupled-mode equations [12], it can be shown that close to the input end the measured value of $r_{\text{meas, mag}}(\tau) = r_{\text{meas, mag}}(xn_g/c)$ is asymptotically proportional to the modulus of the coupling coefficient $|\kappa(x)|$ of the grating. For determining the modulus of the coupling coefficient of the rest of the grating, phase-sensitive OLCR must be used. The condition of losslessness allows us to calculate the OLCR signature one would have obtained from an OLCR measurement from the other side of the device. From both those data, the coupling coefficient of the middle of the grating can then be determined using iterative techniques [3].

F. Reflectivity of DUT in the Frequency Domain Known Analytically

Often the analytical expression of the reflectivity $r(\omega)$ of a DUT is well-known in the frequency domain. This is for example the case for distributed feedback (DFB) lasers. From this information and the source spectrum, which can always be measured, the expected result of an OLCR measurement can be calculated. By adapting this calculated reflectivity to the actually measured one, many important parameters of the DFB laser such as its coupling coefficient κ and the position of a phase jump in its grating can be determined [13].

IV. CALCULATION OF THE REFLECTIVITY OF COMPOUND DEVICES

We have shown that the frequency-dependent reflectivity $r(\omega)$ entirely characterizes any DUT. In most cases, $r(\omega)$ can be calculated using matrix theory [14]. The DUT will be described by a complex scattering matrix, in analogy to microwave engineering. We define the scattering matrix $\boldsymbol{S}$ as

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \boldsymbol{S} \cdot \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

where a_1 and a_2 are the complex electrical field amplitudes of the waves incident from the left and the right, and b_1 and b_2 those exiting the device to the left and to the right, respectively. The frequency-dependent reflectivity of the DUT is then given by $r(\omega) = S_{11}$. In our approach we will not make the transition to the often used transfer matrices, which could cause problems in describing ideal mirrors. The scattering matrix of the DUT can easily be calculated from the scattering matrices of its elements. For any two neighboring elements described by their scattering matrices $\boldsymbol{S}'$ and $\boldsymbol{S}''$, the scattering matrix $\boldsymbol{S}$ of the compound device (Fig. 2) is given by

$$\begin{aligned} \boldsymbol{S} &= \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \\ &= \frac{1}{1 - S'_{22}S''_{11}} \begin{pmatrix} S'_{11} - S''_{11} \det \boldsymbol{S}' & S'_{12}S''_{12} \\ S'_{21}S''_{21} & S''_{22} - S'_{22} \det \boldsymbol{S}'' \end{pmatrix}. \end{aligned}$$

The resulting scattering matrix of a device being composed of more than two elements is calculated by successive elimination of neighboring elements. To illustrate the scattering matrices, examples of some commonly used devices will be given. The scattering matrix of a homogeneous section of optical length d is given by

$$S_{\text{section}} = \begin{pmatrix} 0 & t \exp(-j\omega d/c) \\ t \exp(-j\omega d/c) & 0 \end{pmatrix}$$

where t is the amplitude transmission factor from one end to the other, and c the velocity of light in vacuum. A nonabsorbing mirror of amplitude and phase reflectivities r

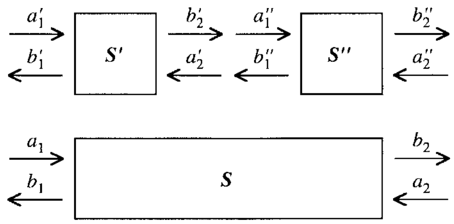

Fig. 2. Adding two two-ports described by their S-matrices.

and φ, respectively, can be characterized by

$$S_{\text{mirror}} = \begin{pmatrix} r\,\exp(j\varphi) & \sqrt{1-r^2}\,\exp(j\varphi) \\ \sqrt{1-r^2}\,\exp(j\varphi) & -r\,\exp(j\varphi) \end{pmatrix}.$$

The scattering matrix of a DFB laser section of length L is given by

$$S_{\text{DFB}} = \begin{pmatrix} r_{\text{DFB}} & t_{\text{DFB}} \\ t_{\text{DFB}} & r_{\text{DFB}} \end{pmatrix}$$

where [12], [15]

$$r_{\text{DFB}} = \frac{-j\kappa\,\sinh(\gamma L)}{\gamma\,\cosh(\gamma L) + [\alpha_g/2 + j\Delta\beta]\sinh(\gamma L)}$$
$$t_{\text{DFB}} = \frac{\gamma\,\exp(-j\beta_0 L)}{\gamma\,\cosh(\gamma L) + [\alpha_g/2 + j\Delta\beta]\sinh(\gamma L)}.$$

The variable γ is given by the dispersion relation

$$\gamma^2 = (\alpha_g/2 + j\Delta\beta)^2 + \kappa^2$$

where κ is the coupling coefficient of the Bragg grating, and α_g its absorption coefficient (which varies with the injection current into the laser). $\Delta\beta$ is the deviation of the propagation constant from the Bragg wavelength, $\Delta\beta = \beta - \beta_0$, with $\beta = \omega n_g/c$ and $\beta_0 = q\pi/\Lambda$, where q is the Bragg reflection order, and Λ is the period of the Bragg grating. For a first order Bragg grating we have $\beta_0 = \pi n_g/\lambda_0$, where n_g is the averaged refractive group index of the grating, and λ_0 is its Bragg wavelength.

V. Superposition of Independent Solutions

Independently superposing solutions cannot be separated in the general case. It is however often possible to do this separation by taking a series of measurements under varying experimental conditions. In other cases, the interference effects between two or more not completely independent paths can give interesting information about the differences in their propagation conditions, which can for example be used to precisely determine the refractive group index difference between the two paths. We will illustrate both these phenomena by one example each.

A. Two Physically Separated Paths

Suppose a beam splitter is inserted in the light path inside the DUT (Fig. 3). In this case, no distinction between the two paths is possible from the reflectogram. We can however note that the two reflections being in different paths, there will be no additional peaks resulting from multiple reflections between the two mirrors. These multiple reflections could however be imitated by adding more beam splitters and thus more independent paths. This shows that in the general case it is not possible to determine which one among several light paths caused a particular reflection peak observed, and often it is not even possible to determine if a given reflectometric signature represents one single light path or rather results of a summation over the reflectometric signatures of several light paths.

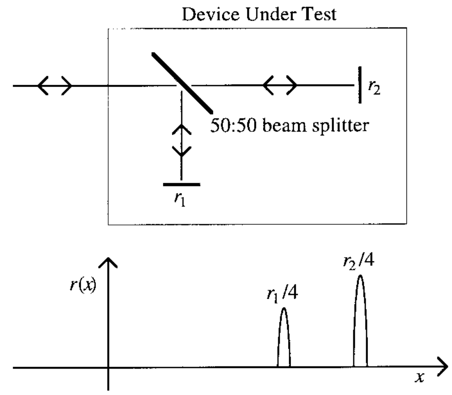

Fig. 3. Physically separated light paths in the device under test.

An example for this kind of multiple paths is coupling into a semiconductor device. As the electromagnetic field distributions in the fiber and the waveguide of the semiconductor device are always slightly different, coupling into the main waveguide mode will be smaller than unity, even in the case of perfect alignment. A portion of the light not coupled into the main semiconductor waveguide mode will often be coupled into other waveguide modes, or in the substrate of the device. When analyzing a semiconductor waveguide using OLCR, we will thus often observe two peaks representing the back facet of the device, corresponding to the reflections at this facet of the light beams propagating in the main waveguide mode and in the substrate. Without any further knowledge, a distinction between the origins of these two peaks is not possible. However, in the case of a semiconductor laser for example, they can be distinguished by making additional measurements, and varying the injection current into the laser [16]. The end reflection peak due to the light propagating in the laser waveguide will experience a much larger gain change with respect to injection current than the light propagating in the substrate. The origins of the two peaks can thus be determined from their amplitude change under different injection conditions. The reflectivity $r(\omega)$ of the device resulting from the superposition of the two paths can be easily modeled by adding their respective reflectivities $r_1(\omega)$ and $r_2(\omega)$.

B. Two Optically Separated Paths

Interference effects can only occur between electrical waves having nonorthogonal states of polarization. In many devices, however, two orthogonal polarization modes propagate, in general under slightly different propagation conditions. In optical fibers, for example, one can define two different refractive group indexes n_{g1} and n_{g2} for the two polarization modes. The relative difference between them is usually small, but is sometimes increased intentionally to avoid coupling between these two polarization modes, as done in polarization preserving fibers. In optical low-coherence reflectometry, the measurement will give the linear sum of the complex reflectivity from both light paths. In the case of a single mode polarization preserving fiber, the scattering centers in the fiber will be the same for both polarization modes, but the respective refractive group indexes will be different. The recombination of the light reflected by the DUT with the light from the reference arm leads to successive intervals of constructive and destructive interferences [10], often characterized by the distance between any two neighboring minima, which is known as the beat length. The difference between the refractive group indexes of the two light paths $\Delta n_g = |n_{g2} - n_{g1}|$ can then be calculated from

$$\Delta n_g = \frac{\lambda_0}{2L_B}$$

where λ_0 is the center wavelength of the light producing the interferences and L_B is the beat length measured in air. If the determination of the beat length is not of interest, polarization insensitive OLCR [10] can be used. This means that the reflected powers in two orthogonal polarization states are measured separately, their sum being independent of the polarization state of the light reflected by the DUT.

VI. Conclusion

It has been shown that the result of an OLCR measurement can always be predicted from the reflectivity of the DUT in the optical frequency domain. Our theory includes effects such as multipath propagation, a problem often encountered in guided-wave optics. We have given many examples of applications of OLCR, and we have shown how they can all be written as specific solutions of our general theory.

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