COHERENCE-DOMAIN REFLECTOMETRY WITH SYNTHESIZED COHERENCE FUNCTION

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1. Introduction

It is generally known that the original OTDR in which tested systems are probed with rather short impulses of rather high power level optical radiation suffers from a trade-off between its two key performance parameters - space resolution and dynamical range. The spatial resolution is becoming better when the testing pulses are getting shorter. But simultaneously the negative consequence is that measurement band-with is increased. This increases the noise levels detected and it results in the significant decrease of dynamical range. And more the shortening of the test impulse implies the decrease of energy available for detection. Since the time of the invention of today already "classic OTDR" by Barnoski and Jensen in 1976 [1] several new techniques and solutions were suggested and analyzed to remove the "trade-off" relation between the performance parameters mentioned above. For the illustration we can mention here briefly [2] a./ the correlation OTDR based on the use of the pseudorandom signal, complementary Golay code, Hadamard biorthogonal code b./ coherent OTDR, c./ photon-counting OTDR, d./ low correlation OTDR , e./ polarization OTDR, f./ coherent optical frequency-domain reflectometry (OFDR) with the linear frequency scanning or with the frequency modulation of the intensity, g./ coherent optical reflectomery with the synthesized coherence function. But it can be stated the most significant and progressive contribution to these new approaches is the Optical Coherence-Domain Reflectometry with Synthesized Coherence Function (OCDR-SCF). Its valuable and most important advantages are that it does not utilize any mechanical moving parts and acquiring of the measurement results is straightforward without any complicated calculation in the frame of signal processing.

The main intention of this paper is the detailed characterization of the OCDR-SCF and the analysis of the procedure for the synthesis of general shape coherence function (CF) especially the δ-like one. At the end the main advantages and drawbacks of CDR-SCF are discussed. The applications of this method in space distribution measurement of several physical quantities are outlined.

2. OCDR-SCF - basic idea and principle

The principle and basic idea of the application of OCDR-SCF in the optical fiber reflectometry can be explained using the simplified block diagram of the measurement system in the Fig. 1. It is really Michelson interferometer excited by the optical coherent laser frequency-swept in a rather broad range. The acousto-optic deflector AOD increases periodically the oscillation frequency ω_o of the deviated beam by ω. The phase modulator P-MOD makes possible to change continually the phase of optical wave in the reference arm in the range of $\pm\pi$. Signals leaving the reference arm and the measuring one are superimposed at the 3 dB beam splitter OBS-2. As for the shape both signals leaving the OBS-2 are quite similar but mutually shifted in phase by π. In such a way it is possible significantly decrease the influence of the source optical radiation noise. The optical radiation coming to the photo-detector PD-1 can be described in the complex representation as follows

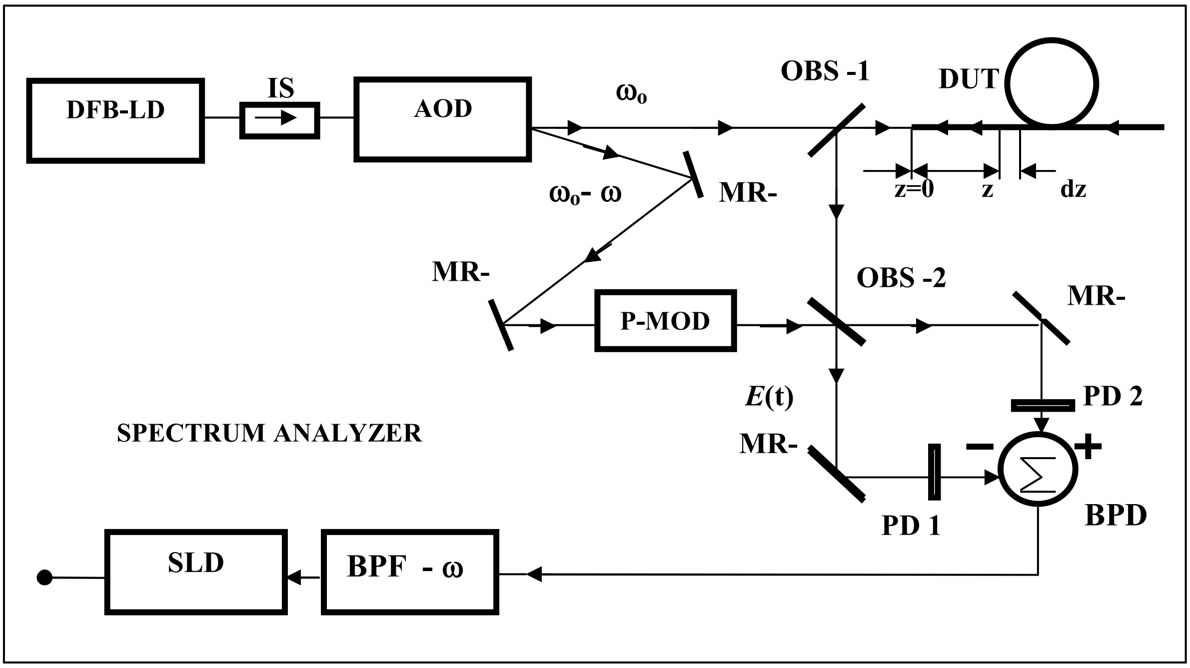


Fig. 1: The simplified block-diagram of the optical reflectometer based on the use of OCDR-SCF: DBF-L – Distributed Feed Back Laser, IS – Optical Isolator, AOD - Acoustic-Optic Deflector, OBS 1,2 - Optical Beam Splitters, DUT-Device Under Test, MR 1-4 – Mirrors, PD 1-2 – Photo-detectors, P-MOD – Phase Modulator, BPD-Balanced Photo-detector, BPF – Band-Pass Filter, SLD – Square Law Detector

$$E(\mathrm{t}) = \mathrm{E_o} \mathrm{e}^{\mathrm{j}[(\omega_o - \omega)\mathrm{t} + \varphi(\mathrm{t})]} + \mathrm{E_o} \int_0^L r(\mathrm{z})\, \delta\mathrm{n}(\mathrm{z})\, \mathrm{e}^{\mathrm{j}[\omega_o \mathrm{t} + \varphi(\mathrm{t} - \frac{2\mathrm{z}}{\mathrm{v_g}})]} . \mathrm{e}^{-\mathrm{jk2z}} \mathrm{dz} \tag{1}$$

The first and second terms in this relation represent the signal from the reference arm and the from measuring one respectively. The second term includes all signals that are back-scattered from all elementary sections dz distributed along the tested fiber. One can see that the amplitudes of scattered signals are directly proportional to the local microscopic fluctuations of the refractive index δn(z) and to the local reflection coefficient r(z) that is to be measured. Eo and ωo are the amplitude and central oscillation frequency of the optical source DFB-L respectively. The phase fluctuations of the optical source described by φ(t) are the random function of time. The symbols vg and k represent the group velocity and the wave number of optical wave in the tested fiber respectively.

The signal from the balanced photo-detector BPD is filtered by the band-pass filter BPF-ω. From the mixing product of the detector only intermediate frequency component ω is selected. The average value of the intermediate frequency signal at the output of the BPF is given by the relation

$$\mathrm{i(t)} = \mathrm{Re}\{\mathrm{K} . \mathrm{E_o^2} . \mathrm{e}^{\mathrm{j}\omega \mathrm{t}} . \int_0^L r(\mathrm{z})\ \delta\mathrm{n}(\mathrm{z})\ [\frac{1}{\mathrm{T}} \int_0^T \mathrm{e}^{\mathrm{j}[\ \varphi(\mathrm{t} - \frac{2\mathrm{z}}{\mathrm{v_g}}) - \varphi(\mathrm{t})]} \mathrm{dt}] . \mathrm{e}^{-\mathrm{jk2z}} \mathrm{dz}\} \tag{2}$$

where K is an appropriate constant.

In such a way the phase fluctuations of the optical source radiation are averaged. These fluctuations can also be equally described by the signal spectral power density. The time integral in square brackets in (2) describes the coherence function γ(z) of the DFB-L. As it is well known the Fourier transform of the optical source coherence function defines also the spectral power density of the source. As a consequence the optical source power spectrum function is uniquely related to its coherence function. So one can say: *to synthesize a suitable coherence function means to create the corresponding time averaged spectrum shape.* Therefore it is very important to examine appropriate possibilities for the shaping of average optical spectrum. It dominantly restricts the space for the synthesis of a required coherence function.

Due to the random microscopic fluctuations of the refraction index along the tested glass fiber the detected back-scattered signal is of random nature not only due to the random phase fluctuations of the optical source but also due to refractive index space fluctuations in fiber core. To take into account these fluctuations it is necessary to use a square-law detector SLD. As it is known its output signal depends on the correlation function <δn(z1)δn(z2)>. The signal P at the output of the SLD is given by the integral

$$P \approx E_o^4 \int_0^L \int_0^L r(z_1)\, r(z_2)\, \gamma(z_1)\, \gamma(z_2) \langle \delta n(z_1)\, \delta n(z_1) \rangle\, e^{-j2k(z_1+z_2)} dz_1 dz_2 \tag{3}$$

The correlation function < δn(z1)δn(z2) > in glass can be roughly approximated with a good accuracy by the Dirac δ(z1-z2) function [3]. Then integral (3) can be reformulated as follows

$$P \approx E_0^4 \int_0^L | r(z) |^2 |\gamma(z)|^2 \, dz \tag{4}$$

The consequences following from this expression are very important. In the case the squared absolute value of the coherence function γ(z) can be shaped similar to the δ(z)-like function then the output signal of the square-law detector is directly proportional to the squared absolute value of the reflection coefficient r(z) that we want to pick-up.

$$P \approx E_0^4 \; | r(z) |^2 \tag{5}$$

From the signal processing point of view the obtained final relation (5) has significant consequences. The indicated implementation of the δ-like SCF means "a direct measurement of the space distribution of reflection coefficient along the DUT is possible". No lengthy calculations in measured signal processing are needed as it is the case at other approaches or methods.

3. The principle of coherence function synthesis

To explain briefly the basic idea of the coherence function synthesis and also due to simplicity we shall consider first the interferometer excitation with an ideal monochromatic laser diode with the central oscillation frequency ωo with no phase fluctuations φ(t), Fig.1. The laser diode injection current is periodically modulated by a symmetrical square waveform function. It is expected that also the laser frequency is modulated proportionally in the same way. The laser frequency is changing stepwise between two frequencies (ωo- ωs/2) and (ωo+ ωs/2) where ωs is the total angular frequency change during one modulation period called the "separation frequency" of the waveform. It is generally known that the correlation function of the two monochromatic harmonic functions shifted in phase by Δφ is proportional to the cos(Δφ). Taking this into account we can state that the correlation function γ(τ) of the above mentioned modulated harmonic signals entering the interferometer arms with the mutual phase shift [(ωs/2)τ] is given by the relation

$$\gamma(\tau) = \cos\frac{\omega_s}{2}\tau \qquad (6)$$

where $\tau = 2z/v_g$ is the round trip delay time between the reference signal and scattered one form the point at the distance z from the input end of the tested fiber. It is to be stressed that the wave number $k = k(t)$ in the measured fiber is also modulated in the same way as the frequency.

Using this elementary result we can gradually generate a set of similar "elementary correlation functions" with the frequencies which are integer multiples of ωs. Of course this requires changing the modulation frequency in an appropriate stepwise way. Through the superposition of these "elementary" coherence functions we can synthesize an arbitrary shape periodic coherence function. Let us consider now the periodical stepwise shape of the laser diode modulation current which will result in directly proportional modulation of the frequency. The frequency response to this current is given in Fig. 2. The frequency increases stepwise by ωs in each step to the maximum value Nωs in N-th step of one period of the modulation function. As it was explained above and in analogy with the basic idea of the Fourier series expansion each modulation step can potentially provide one term of the intended SCF. The whole modulation waveform produces a set of elementary CF described by (7). The generation of these elementary CF is obtained through the process of the subsequent time averaging running through all steps of the whole modulation function period.

$$\cos(\omega s.z/v_g), \cos(2\omega s.z/v_g), \cos(3\omega s.z/v_g), \cos(4\omega s.z/v_g), ..., \cos(N\omega s.z/v_g) \qquad (7)$$

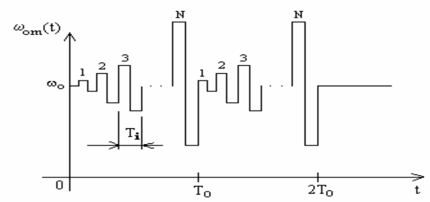


Fig. 2, The stepwise modulation function of the laser source frequency, T_i - duration of i-th step, T_o – the period of the modulation function, N – the number of steps in the modulation function.

If there would be some possibility to adjust the initial phases of the particular terms in (7) they could be used in a similar way as it is done in the theory of Fourier series. Such a phase shift can be realized by the phase modulator driven synchronously with the modulation signal that is proportional to one used for the frequency modulation. The modulator can be placed in the reference arms of the interferometer, see Fig. 1. As a result the functions (7) take the form

$$\cos[\omega s(z-z\zeta)/v_g], \cos[2\omega s(z-z\zeta)/v_g], \cos[3\omega s(z-z\zeta)/v_g], \cos[4\omega s(z-z\zeta)/v_g], ..., \ldots,\cos[N\omega s(z-z\zeta)/v_g] \qquad (8)$$

o synthesize the periodic CF of appropriate form, like i using Fourier series, it is also necessary to implement in each expansion term (8) proper multiplication coefficients. It can be done by a proper adjusting of time length of each step in the frequency and phase modulation waveforms respectively. The duration of each step determines the amplitude of the particular term in the SCF expansion series. As a result the modulation waveform becomes more complicated [4].

4. The synthesis of the δ-like coherence function

In the following we show how the periodic δ-like coherence function can be synthesized. We use the same monochromatic laser source as mentioned above. Its frequency will be modulated by the modulation function depicted in the Fig. 2. Due to the appropriate time averaging the necessary condition for the δ-like coherence function synthesis is that *the duration of any step in the modulation waveform is longer enough as compared with the round trip time delay* $\tau=2z/v_g$. First let us consider the frequency modulation waveform as it is depicted in the Fig. 3 but with the appropriate changing duration T_i of each symmetrical step. According to (2) the output current of the PD can be described by

$$\mathrm{i(t)} \approx \int_0^L r(z)\,\delta\mathrm{n(z)}\{\frac{1}{\mathrm{T_o}}\int_0^{\mathrm{T_0}} \exp\{j[\omega t - \omega_{om}.(t').\frac{2z}{v_g}]\}\,dt'\}\,dz\} \tag{9}$$

Where $\omega_{om}(t')$ describes the frequency modulation waveform that is given by

$$\omega_{om}(t') = \omega_o + \alpha(t').\frac{\omega_s}{2} \tag{10}$$

where ω_o is the central oscillation frequency of the source diode

$$\alpha(t') = \sum_{i=1}^{N} i.[1(t' - \sum_{k=0}^{i-1} T_k) - 2.1(t' - \frac{T_i}{2} - \sum_{k=0}^{i-1} T_k) + 1(t' - T_i - \sum_{k=0}^{i-1} T_k)] \tag{11}$$

where 1(t) represents rectangular step function and T_k the time duration of the k-th step in the modulation function. Of course it holds

$$T_1 + T_2 + \ldots + T_k + \ldots + T_N = T_o \tag{12}$$

and the equation (9) can be rewritten as follows

$$\mathrm{i(t)} \approx \; = \mathrm{Re}\{e^{j\omega t}\int_0^L r(z)\,\delta\mathrm{n(z)}..[\sum_{i=1}^{N}\frac{T_i}{T_o}\cos(i\,\omega_s.\frac{z}{v_g})].e^{-j2k_o z}\}.dz \tag{13}$$

The inner term in squared brackets of (13) represents the SCF γ(z). To make the result more general one can introduce into each elementary term in (13) the "initial phase shift" $\zeta_i = (i.\omega_s/v_g).z_\xi$. It can be done using the appropriate phase shifter. SCF γ(z) can now be written in a final form

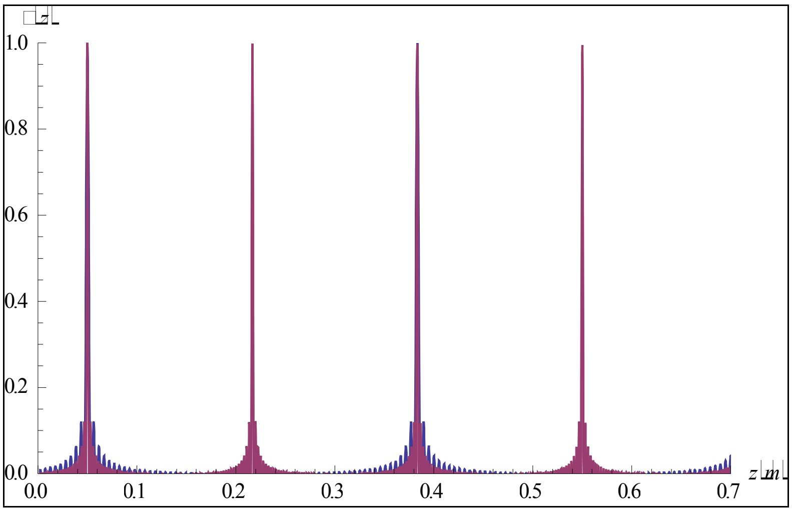
$$\gamma(z) = \sum_{i=0}^{N} t_i \cos(i\,\omega_s.\frac{z}{v_g} - z_0) = \sum_{i=0}^{N} t_i \cos[i\,\omega_s.\frac{(z - z_0)}{v_g}] \tag{14}$$

where term with i=0 represents the DC component of the periodic SCF. t_o is the relative time at the early stages of the frequency modulation waveform when no changes of frequency take place.

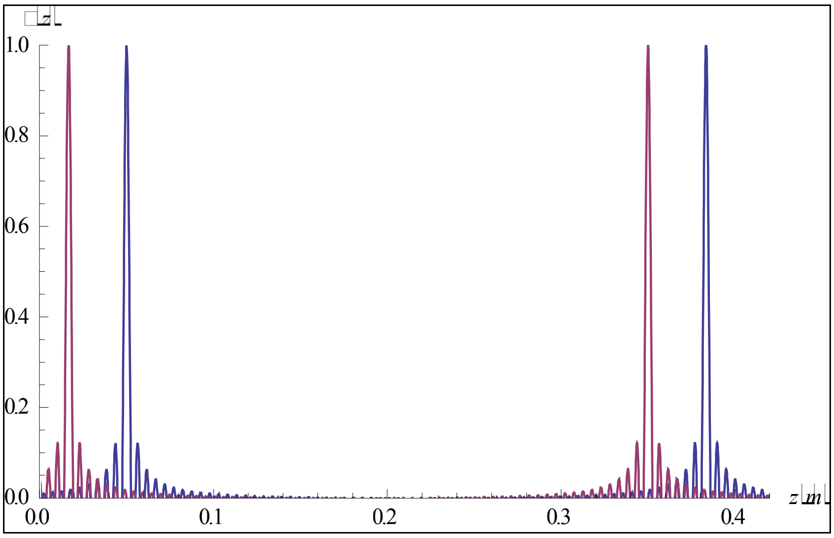
In a special case when the frequency and phase modulation functions are given by a set of symmetrical and time equal steps $T_i = T_o/N$, see Fig. 2, the SCF (14) can be expressed by the relation

$$\gamma(z) = \sum_{i=1}^{N}\frac{T_i}{T_o}\cos(i\,\omega_s.\frac{(z-z_0)}{v_g}) = \frac{\cos[(N+1).\frac{\omega_s}{2}.\frac{(z-z_0)}{v_g}].\sin[N\frac{\omega_s}{2}.\frac{(z-z_0)}{v_g}]}{N\sin[\frac{\omega_s}{2}.\frac{(z-z_0)}{v_g}]} \tag{15}$$

The z-dependence of this function (first two peaks of the periodical SCF), shifted by z_0 = 0.05 m with respect to z = 0, for two frequencies f_s = 600 and 1200 MHz, N = 64 and $v_g = 2.10^8$ m/s are drawn in the Fig. 3 a. Fig. 3 b declares the first peak position shift using the phase shifter for the separation frequency f_s = 600 MHz.



(a)



(b)

Fig. 3, The synthesized δ-like CF and its peaks positions realized through the scanning of the separation frequency f_s (shown for $f_s = (\omega_s/2\pi)$ = 600, 1200 MHz, first two peaks) while the phase shift is constant z_0 = 0,05 m (a) and through the scanning of phase shift (shown first peak for z= 0,05, 0,35 m) for the constant separation frequency $f_s = (\omega_s/2\pi)$ = 600 MHz (b).

5. OFDR-SCF main performance parameters

The OCDR-SCF is a very efficient tool for many sensor applications mainly due to its potential excellent performance parameters and a straightforward acquiring of the measurement results. No special calculations are needed as it is the case at other methods. Except others the measurement system does not need any moving parts like scanned mirrors or so. The δ-like CF peak can be shifted along the measured fiber through the changing of the modulation function separation frequency f_s. It is to be stressed that it is rather complicated task. The measurements in the close vicinity of z = 0 are not accessible. Second, the space resolution depends on the frequency magnitude f_s. As a result the space resolution is not the

same along the fiber. It is changing from point to point. Another possibility for the SCF peak scanning is the use of phase shift. It can be realized very easy and it doesn't suffer from any similar drawbacks. The measurement by this method is faster as it is in the case of other available methods. The measurement time within one period of the modulation waveform takes approximately a few tens of μs [5]. The sensitivity and also the dynamical range of this method are mostly determined by the heterodyne detection scheme. The accessible sensitivity can be better than –130 dBm. Moreover the method does not suffer from the dead zone caused by strong Fresnel reflections. They are eliminated by the narrow coherence function. The dynamical range of this method is limited mainly by the existence of SCF sub-peaks.
The space resolution is determined by the full width at half maximum (FWHM) of the main peak of the coherence function. It can be derived from the relation (13) and is approximately given by the relation

$$\Delta z_{res} = \frac{v_g}{Nf_s} \tag{18}$$

The peaks period defines the measurement range that is given by

$$\Delta z_{range} = \frac{v_g}{f_s} \tag{19}$$

The space resolution of the method increases with the increasing number of steps in one period of the frequency modulation function and the separation frequency ωs of the first step of the modulation function. In the contrary the measurement range is defined only by the separation frequency in the first step of the modulation function.
From the experimental point of view the most significant problems concern the non-linearity between the injection current amplitude and the optical frequency of laser diode and the frequency response to the modulation waveform (transients). Both factors can be compensated by the pre-distortion of the current modulation waveform and by the use of special optical filters and optical gratings [6]. Lately new optical sources – Super Structure Gratings Distributed Bragg Reflector Laser Diodes have been developed and are being now used in CDOR-SCF [7].

6. Conclusion

The description of the realization of the synthesized coherence function and its potential application in optical coherent reflectometry with synthesized coherence function (OCDR-SCF) was given. The advantages and drawbacks of the OCDR-SCF were briefly analyzed and partially compared with classical OTDR. The OCF-SCF is very perspective method. In the recent time several sophisticated applications of this method for the measurement of space distribution of various physical quantities like stress, tension, torsion, temperature have been realized [8,9,10]. This method is permanently developing and an intensive effort in world research laboratories is devoted to its further improving and perfection [8,9,10].

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8. References

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