OPTICAL CORRELATION REFLECTOMETRY WITH SYNTHESIZED COHERENCE FUNCTION AND ITS EXTRACTION BY COHERENCE SYNCHRONIZATION

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1. Introduction

Optical time domain reflectometry (OTDR) is an important tool in the diagnostics of the current sophisticated optical fiber transmission systems. However classic OTDR suffers from some limitations and drawbacks, mainly due to the "trade-off" between the measurement range and space resolution. As a result it was rapidly developing and many new modifications of this method were occurring along the last decades. About ten modifications or new versions of this reflection method had been developed and introduced into practical applications. We can remind here e.g. Low Correlation OTDR, Complementary correlation OTDR, Correlation OTDR with the use of pseudorandom signal, Coherent OTDR, Low Coherent OTDR, Photon Counting OTDR, Polarization OTDR, Coherent Frequency Domain Reflectometry and others [1]. All these modifications have some advantages and disadvantages as for the performance parameters mentioned above and are suitable more or less for special applications. Special groups of these modifications are also those based on optical correlation domain reflectometry (OCDR).

OCDR is significant due to the fact that it is not limited by the bandwidth of the optical receiver as it is the case in several other OTDR modifications. OCDR is based on mixing of the measured reflected signal and the reference one and the difference frequency component modulated by the backscattered or reflected local light on the fiber under test (FUT) is detected. In this method the spatial resolution is principally determined by the frequency band width of the optical source. The broader is the bandwidth the better is the space resolution [2, 3]. But on the other side simultaneously the measurement range is getting worth. The grater is the bandwidth the smaller the measurement range. One of the possibilities how to partially solve that problem is the application of the synthesized coherence function of the laser source synthesized by the appropriate frequency modulation of the source [4, 5]. This function is a periodic one and the measurement range is determined by the length of the first period which is given by the parameters of the step-like frequency modulation function and as a result it can be adjusted to a required value.

In this paper we provide a solution to the extension of measurement range of the OCDR based on the combination of applications of the "synthesized coherence function (SCF)" and gating of local reflection signal on FUT by the artificial synchronization of the phase modulation functions in reference arm and measured one. In such a way it is possible to enhance the measurement range beyond the first period of the SCF.

In the second section the principles of the OCDR based on the combination of the SCF and testing signal gating by the artificial coherence of the phase modulation functions in the reference and measuring arm is described in details.

Third section is devoted to the explanation of the generation of the SCF and how its parameters depend on the frequency modulation and to the relation between the measurement range and the space resolution. Finally there is a brief main results summary.

2. Principles of signal gating by the coherence synchronization

As it was stated above the main restriction of the basic low coherence OTDR concerns its measurement range. It is the consequence of testing signal low coherence length [4,5]. The lower is the correlation length the better the space measurement accuracy. On the other hand high measurement range requires long coherence length. This problem was partially solved by the utilization of the synthesized coherence function [4], which is characteristic by the periodic correlation peaks. The achieved space resolution of this method is significantly improved as compared with a classic low coherent OTDR. But the measurement range is still limited by the separation between periodic correlation peaks. Due to the periodicity only the first period can be utilized. The method of the coherence synchronization we are going to describe overcomes this shortage.

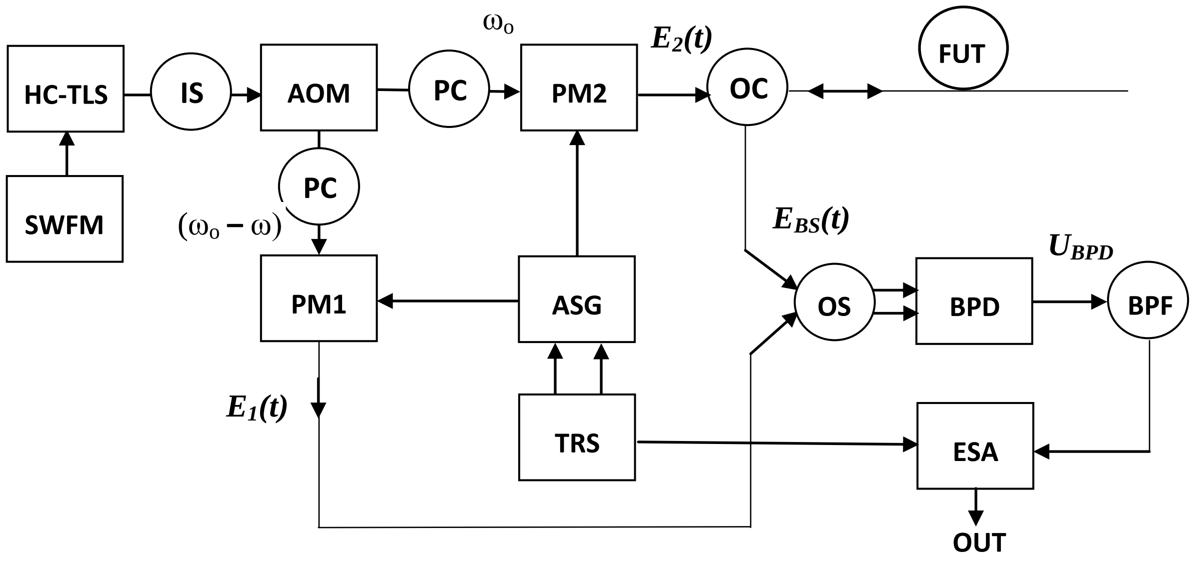

Fig.1: *The simplified diagram of the C-OTDR reflectometer based on the coherence synchronization, HC TLS – high coherence tunable laser source, SWFM – step-wise frequency modulator of HC-TLS, IS – isolator, AOM – acousto-optic modulator, PC – polarization controller, PM1, PM2 –light phase modulators, OC – optical circulator, FUT – fiber under test, ASG – arbitrary signal generator, TRS - trigger source, OS - 3-dB optical splitter, BPD – balanced photodetector, BPF – bandpass filter, ESA – electric spectrum analyzer*

The basic idea of the coherence OTDR with the synthesized coherence function of the probe signal and the signal processing based on the coherence synchronization of the probe and signal coherence functions can be explained using Fig. 1.

First let us consider we have high coherent tunable laser source HC-TLS, see Fig. 1, with the spectral band width of cca 1 kHz providing the light coherence length in km range. Due to coherent detection based on the signal mixing on the photodiode of balanced photodetector BPD, which generates the frequency difference signal component ω, the acousto-optic modulator AOM is placed into light path. Light from one arm of the AOM at central frequency ω_o, launched through the polarization controller PC, phase modulator PM2 and optical circulator C into fiber under test FUT, represents the testing signal $E_2(t)$. The measured back scattered signal from the FUT is directed by the optical circulator OC and symmetrical optical splitter OS to the balanced photodetector BPD. The reference signal $E_1(t)$ from the AOM at frequency $(\omega_o - \omega)$ is launched through the polarization controller PC, phase modulator PM1 and OS into second input of the BPD. Electric field intensities of the linearly polarized signals - reference $E_1(t)$ and testing $E_2(t)$ can be expressed as

$$E_1(t) = E_{SR}.exp\{j[(\omega_o\text{-}\omega)t + s(t)]\}.exp[j\alpha(t)] \tag{1}$$

$$E_2(t) = E_{SR}.exp\{j[\omega_o t + s(t)]\}.exp[j\beta(t)] \tag{2}$$

where ESR is the amplitude of the electric field of the laser source. The frequency of the laser source is modulated through its electric current amplitude modulation by the stepwise modulation function s(t) which, as we shall see later, is responsible for the generation of the periodic narrow peak autocorrelation function of the laser source. Besides the acousto-optic modulator AOM causes the negative phase change (-ωt) in $E_1(t)$. The phase modulators PM1 and PM2 generate phase modulations described by the phase modulation functions β(t) and α(t) respectively. β(t) and α(t) are the arbitrary stepwise wave form functions generated by arbitrary signal generator ASG with two controlled outputs, Fig. 2. These functions are arbitrary pseudorandom functions with the constant width of one step Δt and triggered or started by the trigger source that can control the time delay between these functions. Generated phase changes are accidental white noise like values from the interval [+Φ, -Φ] with the homogeneous constant probability density function given as p(t) = [1/(2Φ)], Fig. 2. In such a way one can destroy the coherence of the laser source artificially. As a consequence, as it will be shown later, if the time delay of the phase modulation functions β(t) and α(t) is adjusted properly, the correlation function of these functions enables us to extract the reflected light at any point of FUT.

The resulting measured light $E_{BS}(t)$ simultaneously backscattered from all positions of FUT can be described as the convolution of the test signal $E_2(t)$ and the reflection coefficient distribution ρ(t) along the FUT as follows

$$E_{BS}(t) = \int \rho(\tau).E_2(t-\tau)d\tau \quad , \tag{3}$$

where τ is the delay time corresponding to the positon "z" on the FUT according to the relation $\tau = (2z/v_g)$, where v_g is the light group velocity in the FUT. The harmonic signal U_{BPD} of the difference frequency ω at the output of the balanced photodetector, see Fig.1, has the amplitude given by the following relation

$$U_{BPD} = e^{j\omega t}\int \int\{\frac{1}{T}\int\left[E_{SR}.e^{j[s(t)+\omega_o t+\alpha(t)]}\right]^*\left[E_{SR}.e^{j\{s(t-\tau)+\omega_o(t-\tau)+\beta(t-\tau)\}}\right]dt\}\rho(\tau)\,d\tau =$$

$$= e^{j\omega t}\int \rho(\tau)\; I_1(\tau)\, I_2(\tau)\, d\tau \tag{4}$$

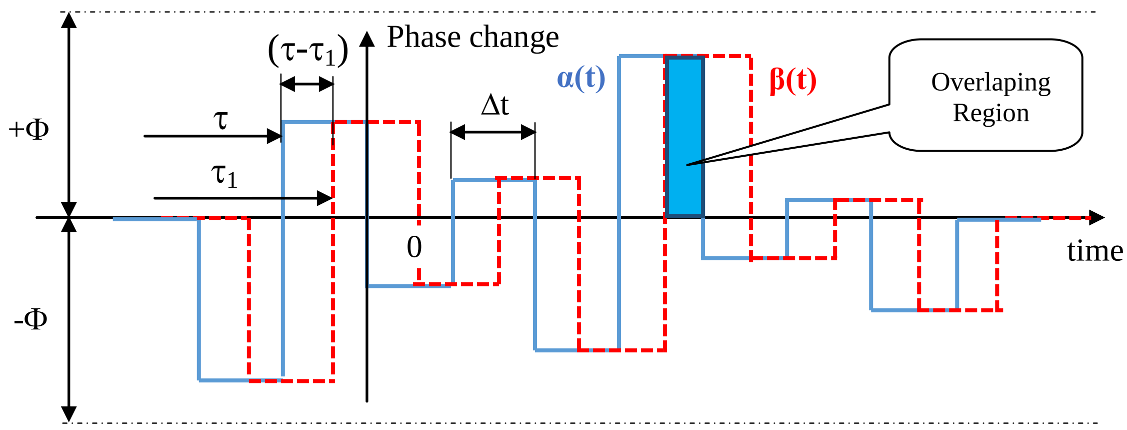

Fig. 2: *Arbitrary („white-noise" like) phase modulation functions α(t), β(t) delayed in time by (τ-τ₁).*

For integrals $I_1(\tau)$ and $I_2(\tau)$ included in (4) we can write following relations

$$I_1(\tau) = \frac{1}{T}\int \left[E_{SR}.e^{js(t)}\right]^* \left[E_{SR}.e^{j\{s(t-\tau)-\omega_o\tau\}}\right]dt \qquad (5)$$

$$I_2(\tau) = \frac{1}{T}\int e^{j[(\beta(t-\tau)-\alpha(t)]}dt \qquad (6)$$

Integral (5) represents the autocorrelation function of the frequency modulated laser source by modulation function s(t) which is phase shifted by ($-\omega_o\tau$). Integral (6) is the mutual correlation function of the phase modulation functions $\alpha(t)$ and $\beta(t)$ of the reference signal and the probe signal respectively.

As it follows from the (4) and (5), (6), if we choose the position on the FUT defined by $z_1 = (\tau_1.v_g)/2$ and adjust the time delay of the waveform modulation function $\alpha(t)$ in the reference arm to the value τ_1 by use of the trigger source TRS, so that $\beta(t) = \alpha(t)$, the cross correlation of these phase modulation waveforms acquires the narrow pulse form or the "gate form" and as a consequence it can extract the source autocorrelation function of the probe light at the position z_1 as a source of the local backscattered light. In other words under this condition the noise-like phase modulations functions $\beta(t)$ and $\alpha(t)$ are synchronized at point "z_1" and the cross correlation of $\beta(t-\tau_1)$ and $\alpha(t)$ creates the "extraction gate" for the local autocorrelation of the probe light. The form of this extraction gate will be briefly described as follows.

The correlation function $I_2(\tau)$ can be calculated as the time integral from $-\infty$ to $+\infty$ as a function of time delay τ. The time dependence of the arbitrary wave form modulation function in the vicinity of $\tau = \tau_1$ is depicted in the Fig. 2. There are there two accidental and identical functions mutually delayed in time by ($\tau-\tau_1$). Integral (6) which represents a time mean value can be evaluated much more simply if we exchange these random time functions by the repeated realization of the corresponding statistical process and then we can calculate this mean value using the corresponding probability density functions of the phase shift values. Of course it is possible only under the conditions that the statistical process is "the ergodic process". This fact allows us to calculate the mean value as one calculated from the repeated realization of statistical process in which two coupled (dependent) or not coupled (independent) values of the possible phase shifts (φ_1,φ_2) are counted. Due to the white noise like homogeneous statistical process of the phase occurring from interval [$-\Phi,+\Phi$] the resulting probability density function is given by the product of the [$1/(2\Phi)$] and the time length of the particular time interval. In our case the relative /overlapping/ time interval in which $\varphi_1=\varphi_2$ (mutually dependent values or the same values) is given by $\{[1-|\tau-\tau_1|]/\Delta t\}$, see overlapping region in Fig. 2. Similarly in relative time of no overlapping in one step Δt, where the phases are independent or $\varphi_1\neq\varphi_2$, it is given by $[|\tau-\tau_1|/\Delta t]$. So the resulting probability density functions for "dependent interval" is given by $p_1(\varphi_1,\varphi_1) = \{[1-|\tau-\tau_1|]/\Delta t\}.[1/(2\Phi)]$, see Fig. 2. The presence of expression $\{[1-|\tau-\tau_1|]/\Delta t\}$ in the $p_1(\varphi_1,\varphi_2)$ reflects the fact that this dependence between (φ_1,φ_2) is valid only in this relative time interval. Similarly for the independent couples ($\varphi_1\neq\varphi_2$) in corresponding time interval the probability density function is $p_2(\varphi_1,\varphi_2) = \{[|\tau-\tau_1|]/\Delta t\}.[1/(2\Phi)]2$. Of course the total probability density function $p_{12}(\varphi_1,\varphi_2)$ valid for the whole possible overlapping interval Δt is the sum of $p_1(\varphi_1,\varphi_1)$ and $p_2(\varphi_1,\varphi_2)$. That is $p_{12}(\varphi_1,\varphi_2) = \{[1-|\tau-\tau_1|]/\Delta t\}.[1/(2\Phi)](\varphi_1=\varphi_2) + \{[|\tau-\tau_1|]/\Delta t\}.[1/(2\Phi)]^2$ for $|\tau-\tau_1| \leq \Delta t$.

For the time delay longer than Δt that is for $|\tau-\tau_1| > \Delta t$ it holds $\varphi_1\neq\varphi_2$ and the probability density function is equal to $p_{12}(\varphi_1,\varphi_2) = [1/(2\Phi)]^2$.

Using these probability functions we can write for the integral (6) the following relation

$$I_2(\tau) = \frac{1}{T}\int e^{j[(\beta(t-\tau)-\alpha(t)]}dt = \int_{-\Phi}^{+\Phi}[p_{12}(\varphi_1,\varphi_2)\ .e^{j[\varphi_1-\varphi_2]} + p_{12}(\varphi_1,\varphi_1).e^{j[\varphi_1-\varphi_1]}.dp_1dp_2 \qquad (7)$$

Applying the above relation (7) as the sum of the particular probability density functions and choosing $\Phi = \pi$, it can be easily shown that the integral (8) can be described as

$$I_2(\tau) = I_{GAT}(\tau) = \{ [1-|\tau - \tau_1|]/\Delta t\} \quad \text{for} \quad |\tau - \tau_1| \leq \Delta t \tag{8}$$

$$I_2(\tau) = I_{GAT}(\tau) = 0 \quad \text{for} \quad |\tau - \tau_1| > \Delta t$$

The graphical interpretation of that "gating function" is depicted in Fig. No. 3.

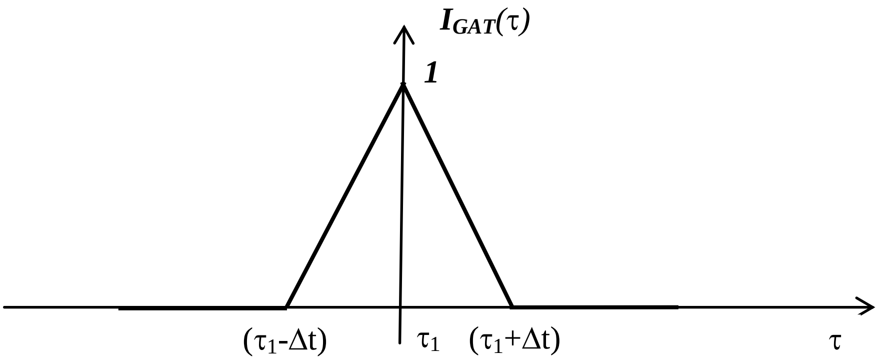

Fig. 3: *The shape of the "extraction gate" obtained by the synchronization of the phase modulation functions of the testing signal and the signal in reference arm.*

3. Synthesis of the coherence function of the test signal

As it was already stated in C-OTDR there is a "trade-off" between the space resolution and the measurement range. It can be partially avoided by the artificial synthetization of the laser source autocorrelation function [1]. Let us propose we have a narrow band tuneable laser source with the central frequency ω_o which can be frequency modulated as it is depicted in the Fig. 4. In this case the central frequency ω_o is periodically modulated by symmetrical stepwise function with the period T_o. Each period T_o includes N symmetrical steps. In the first step frequency change is $(\pm\omega_s/2$ ("+" in the first half and "–" in the second half of the sub period T), in the second one $2.(\pm\omega_s/2)$ and in the last N-th step it is $N.(\pm\omega_s/2)$.

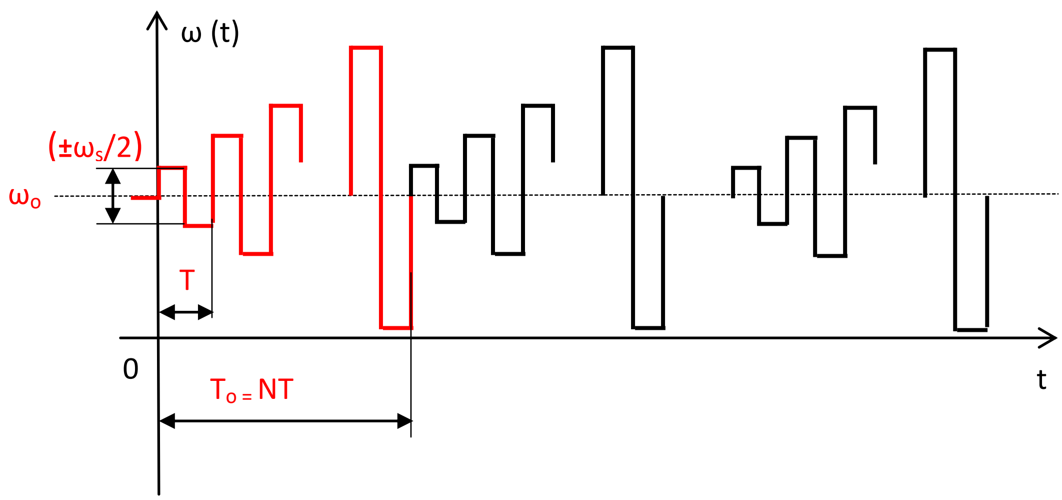

Fig. 4: *Periodical stepwise frequency modulation function of the laser source, one step period is T and the total period T_o, $T_o = NT$*

Under the condition that the *one step period T is much more longer than the roundtrip time*, $\tau_{RT} = 2L/v_g$, of the signal propagating in forward and backward directions along the FUT (L is the length of FUT, v_g is the group velocity of the light in the FUT) the autocorrelation function of our frequency modulated source signal can be seen as the sum of the autocorrelation functions of N harmonic functions with frequencies $(n.\omega_s/2)$, where "n" is an integer, $n \in < 1, N >$. As it is generally known the autocorrelation function of one of these harmonic components in our signal is proportional to $\cos[(n_i.\omega_s/2).\tau]$, where τ is the time delay between the frequency modulated signal in reference arm and one in FUT. So as a result the frequency modulated laser source autocorrelation function $I_1(\tau)$ as it follows from (5) can be described as

$$I_1(\tau) = \frac{1}{T}\int\left[E_{SR}.e^{j[s(t)}\right]^*\left[E_{SR}.e^{j\{s(t-\tau)-\omega_o\tau)}\right]dt \;= \sum_{-N}^{+N}|E_{SR}|^2\, e^{-i\left[\omega_o\tau\; + n\frac{\omega_s}{2}\tau\right]}\;.$$

The summation in the expression above can be replaced by closed form relation as follows

$$I_1(\tau) = |E_{SR}|^2\frac{1}{N}.\cos[(N+1)\frac{\omega_s}{2}\,\tau].\frac{\sin[N\frac{\omega_s}{2}\tau]}{\sin[\frac{\omega_s}{2}\tau]} \tag{9}$$

It is a peak like periodic function with the distance between the neighboring peaks Δz_p (period) determined by the step frequency change ($\pm$ ωs/2) and group velocity as $\Delta z_p = (2v_g/f_s)$. In Fig. 5 there are shown two peaks with the distance 20 mm. The gating effect of the synchronization of the phase modulations functions in the reference and signal arms is in more details demonstrated in the Fig. 6 by the adjusted extraction width Δz_{gate} . The time step of the phase modulation

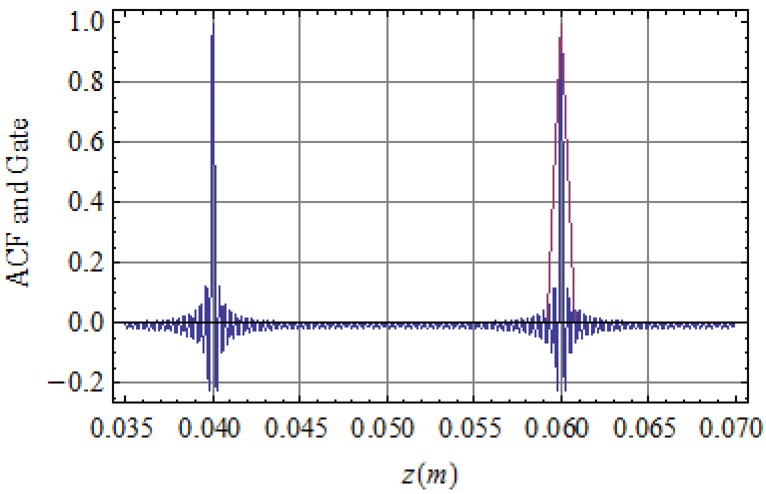

Fig. 5: *First two peaks of the laser source periodic autocorrelation function with the "gate" at the second peak position*

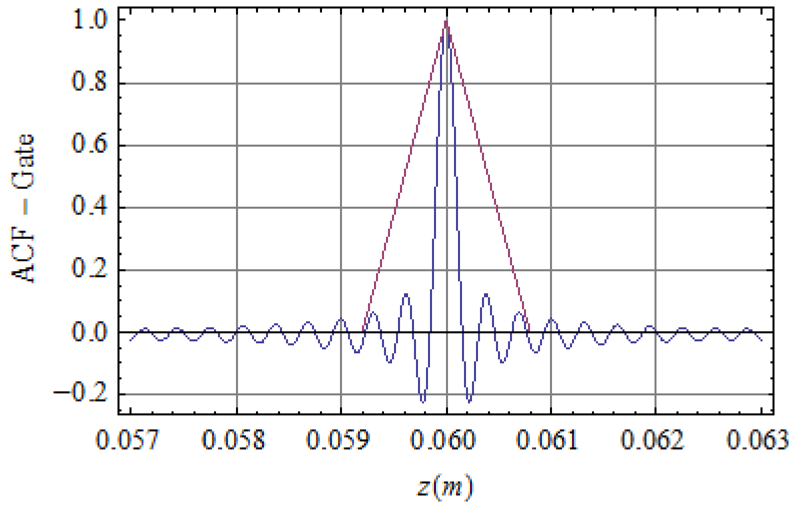

Fig. 6: *Detail position of the "gate" with respect to the second peak of the synthesized autocorrelation function*

artificial wave form is chosen $\Delta t = 10^{-10}$ s what corresponds with the gate width Δ_{zgate} = 0,4 mm which is longer as the theoretical width of the ACF given by $\Delta_{zex} = (2v_g/Nf_s)$ = 0.3125 mm (v_g = 2.10^8 m/s, N=64, f_s = 10 GHz). So it demonstrates a comfortable method for the extraction of the reflected signal at any position of the reflected signal along the fiber. The position of the ACF peak on the fiber can be shifted by the frequency f_s or by the choice of the different peaks of ACF. However the negative fact is that the space resolution or theoretical ACF width depends on the step frequency f_s so the measurement precision depends on the position.

4. Conclusion

At present time OCDR plays an important role in the development of the efficient modifications of the OTDR based measurement systems for the diagnosis of the optical fiber systems and also for the construction of the fiber optic sensor systems for the space distribution of various physical quantities.

In our paper we analysed and described a new sophisticated approach to the improvement of the measurement range of the OCDR in a way that is not in a significant contradiction with the space resolution as it was before. The approach to this problem solution is based on the combination of the application of the synthesized coherence function of the laser testing signal and the controlled signal gating. The signal gating or the local backscattered light extraction from the measured total backscattered light in FUT that is defined by the position of the SCF is approached by the artificial synchronization of the phase modulation functions in measuring and reference arm of the interferometer. In such a way the position of the measured backscattered light is not limited only to the first peak of the SCF but can be also adjusted to other peaks by the proper choice of the time delay of the arbitrary phase modulation functions. In such a way the range of measurement can be enlarged. The drawback of the method is that the space resolution is not independent on the position on the FUT.

Acknowledgement

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