Теория сигналов и систем

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Scattering of the optical pulses on multiple micro-resonator band-stop filters

Pulses' envelopes scattered on several Micro-resonator band-stop filters were examined in the optical transmission line. The most widespread optical pulses have been studied. The possibilities of pulses' time manipulation with various carrier frequencies are showed. New approaches to the indistinguishable pulses' separation have been proposed by means of transformation in to observable ones distinguished by amplitudes or time. A compression possibility has been shown for the chirped pulses. Reference 8, figures 8.

Keywords: *Band stop filter, microresonator, Gaussian optical pulse, super-Gaussian pulse, rectangular pulse, soliton-like pulse, sinc pulse, Lorentzian pulse, exponential pulse.*

Introduction

Today various 3-d optical elements for envelops are applied in order to provide management of optical pulses. They include prisms, diffraction grating pairs, chirped mirrors and and some others [1-3]. The filters on the dielectric micro-resonators can be used for changing of the optical pulses too [4, 5]. In contrast to the traditional devices, the optical filters are widely used for integral processing of the optical circuits' manufacturing, however their capabilities of scattered pulses shaping are currently insufficiently investigated.

Compression and time manipulation of the pulses in the optical fibers can be used according to the application of the several band-stop filters on micro-resonators with whispering gallery oscillations. Such technique allows realizing quasi-one-dimensional structures with comparatively small dimensions.

The goal of the current article is the investigation of optical pulses manipulation by using several band-stop filters. A few band-stop filters with nonoverlapping frequency bands are considered. It has been demonstrated that such structures are characterized by pulses' compression and time manipulation as well as extracting discernible signals from indistinguishable pulses.

1. Statement of the problem

Let's supposes that we have a few (in the general case N) band-stop filters, situated in the optical transmission line (Fig. 1, a). Every band-stop filter consists of S ring micro-resonators and have a frequency band is not coinciding with others.

The goal of the current article is the investigation of optical pulses scattered on this multielement system of band-stop filters.

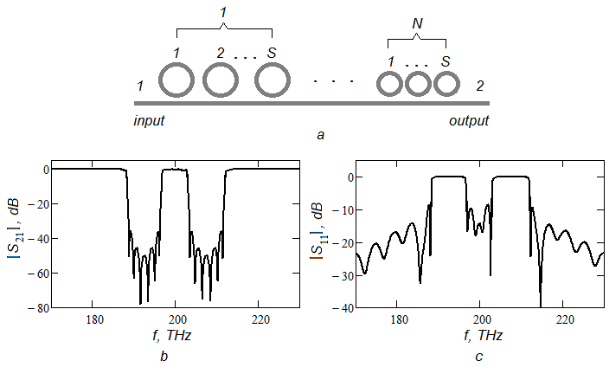

Fig. 1. System of the N band-stop filters on S ring micro-resonators with whispering-gallery oscillations in the optical waveguide (a). Frequency response of the transmission coefficient (b); the reflection coefficient (c) - of two of 10-section filters

2. Green's functions of the band-stop filter systems

For the purpose of optical pulses shapes calculation in the time region, it's necessary to make a Green's functions of band-stop filter system. According to [6], in case of mismatched frequency bands, the transmission coefficient T and the reflection coefficient R of the system can be presented in form:

$$T_\sigma(\omega) = \prod_{v=1}^{N} T_v(\omega) e^{-i(N-v)\Gamma\Delta z}; \quad (1)$$

$$R_\sigma(\omega) = \sum_{v=1}^{N} R_v(\omega) e^{-i2(v-1)\Gamma\Delta z}. \quad (2)$$

Where Γ - is the longitudinal wave number of the transmission line; Δz is the distance between adjacent filters. $T_v(\omega)$, $R_v(\omega)$ define the contribution of scattering coefficients of v-th filter [5]:

$$T_v(\omega) = \sum_{s=1}^{N} \frac{A_{vs}^{+}}{Q_{vs}(\omega)}; \qquad (3)$$

$$R_v(\omega) = \sum_{s=1}^{N} \frac{A_{vs}^{-}}{Q_{vs}(\omega)}. \qquad (4)$$

The amplitudes $A_{vs}^{\pm}$ were calculated according to the proposed technique [4]; $Q_{vs}(\omega) = \omega/\omega_{v0} + 2iQ^D\left(\omega/\omega_{v0} - 1 - \lambda_{vs}/2\right)$; where $Q^D = 1/tg\delta$; $tg\delta$ - is the dielectric loss tangent of the micro-resonator`s material; λ_{vs} - is the eigenvalue of the coupling operator: K_v [4], ($s = 1,2,...,S$); ω - is the current angular frequency; ω_{v0} - is the free oscillation's angular frequency of each insulated micro-resonator in the line of the v-th filter.

The received above relations (1 - 4) were used for the temporal Green's functions' calculation for the waves are reflected in the direction of the source:

$$g_{\sigma}^{-}(\tau) = \sum_{v=1}^{N} g_{v}^{-}(\tau - 2(v-1)\Delta t) \qquad (5)$$

where, from [5], the following expression is true for any filter:

$$g_v^{-}(\tau) = \begin{cases} \dfrac{i\omega_{v0}}{1+2iQ^D} \sum\limits_{s=1}^{S} A_{vs}^{-} e^{i\omega_{vs}\tau}, \tau \geq 0 \\ 0, \tau < 0 \end{cases} \qquad (6)$$

ω_{vs} - is the complex angular frequency of s-th coupling oscillation of the v-th filter of the micro-resonator system in line; $\omega\Delta t = \omega n_{eff}\Delta z / c$. The time-dependence of the Maxwell's equations' solutions is proposed to be equal to $\exp(+i\omega t)$.

The results of the S-matrix frequency responses' ($|S_{11}| = 20\lg|R|$; $|S_{21}| = 20\lg|T|$) calculations are showed at fig. 1, (b), (c) according to the expressions (1 - 4) for two band-stop filters on 10 ring micro-resonators. The frequency of the filter isolated in the line of micro-resonators is supposed to be equal to $f_{01} = 192{,}5$ THz and $f_{02} = 207{,}5$ THz. The central frequency of the structure is $f_0 = 200$ THz (fig. 1, b, c). The dielectric quality factor of the resonator's material constitutes $Q^D = 1/tg\delta = 5 \cdot 10^3$. The distance between adjacent micro-resonators' centers of the filter was supposed to be $21\pi/(2\Gamma)$. The mutual coupling coefficients for non-propagating waves are considered to be unequal to zero only between adjacent micro-resonators: $k_{sn} = 0{,}015$,as well as the coupling coefficients between nonadjacent micro-resonators for propagating waves of the transmission line. The coupling coefficients on the propagating waves are identical and equal: $(\tilde{k}_{sn})_0 = 0{,}015$.

3. Pulse envelops' calculation

The presented relations (5, 6) are used in order to find the general analytic expressions for pulse shapes $E_{out}^{-}(t)$ scattered on band-stop filter's system in the incident direction:

$$E_{out}^{-}(t) = \sum_{v=1}^{N} E_{vout}^{-}(t - 2(v-1)\Delta t) \qquad (7)$$

where $E_{vout}^{-}(t)$ is the pulse envelop is reflected from v-th band-stop filter calculated in [5].

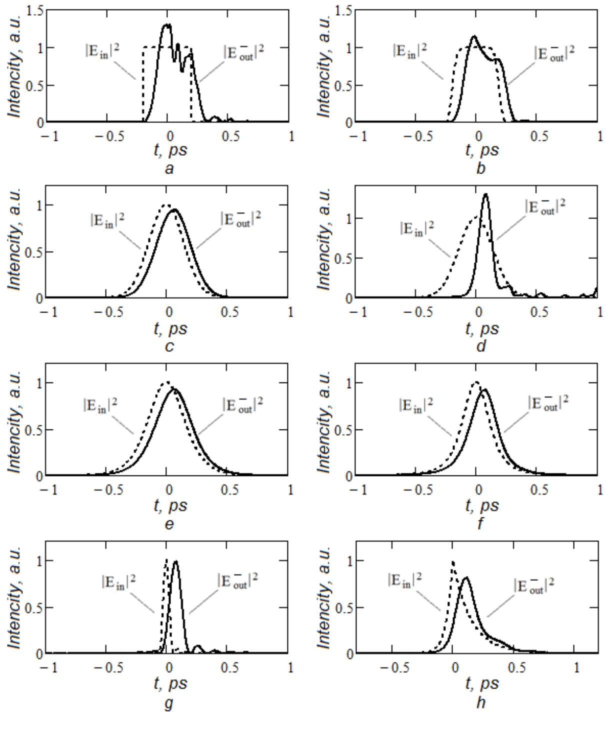

Fig. 2. The shapes of the pulses scattered on two band-stop filters: (a) - rectangular pulse of 0,4 ps; (b) - super-Gaussian pulse ($\sigma = 0{,}2$ ps; $m = 4$); (c) - Gaussian pulse ($\sigma = 0{,}2$ ps; $C = 0$); (d) - chirped Gaussian pulse ($\sigma = 0{,}2$ ps; $C = 0{,}5$), (e) - soliton-like ($\sigma = 0{,}2$ ps); (f) - Lorentzian ($\sigma = 0{,}2$ ps); (g) - ultra-short sinc - pulse ($\sigma = 2$ ps; $N_i = 50$); (h) - exponential pulse ($\sigma_1 = 0{,}1$ ps; $\sigma_2 = 0{,}3$ ps)

The fig. 2 demonstrates the result of scattering on two band-stop filters for various shapes of pulses at fig. 1:

1) For the case of the rectangular envelop of the incident pulse (fig. 2, a):

$$E_{in}(t) = \theta(t - t_1) - \theta(t - t_2);$$

where $\theta(t)$ – is the Heaviside step function [8].

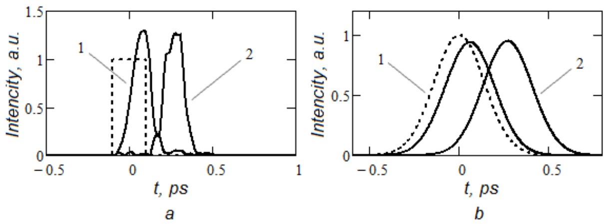

Fig. 3. Scattering of the rectangular (a) and Gaussian (b) optical pulses of various carrier frequency on two band-stop filters: 1- $\Omega = \omega_{01} = 2\pi f_{01}$ **; 2-** $\Omega = \omega_{02} = 2\pi f_{02}$

2) For the super-Gaussian pulse (fig. 2, b):

$$E_{in}(t) = e^{-1/2(t/\sigma)^{2m}}$$

Where the parameter m stands for front steepness and σ – is the width of the pulse envelop [7];

3) For the Gaussian pulse envelop (fig. 2, c-d):

$$E_{in}(t) = \frac{1}{\sigma} e^{-\frac{1+iC}{2} \cdot (\frac{t}{\sigma})^2}$$

(The constant C defines a chirp as a magnitude of frequency modulation of the pulse carrying [7]);

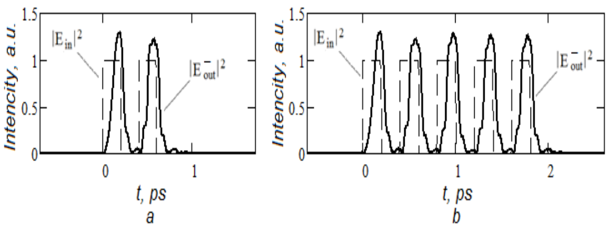

Fig. 4. Mutual influence of the rectangular pulses reflected from two micro-resonator filters (The duration of each incident pulse is equal to 0,2 ps; the temporary interval between adjacent pulse centers is $\delta t = 0{,}4$ **ps)**

4) For the soliton-like pulse (fig. 2, e):

$$E_{in}(t) = \mathrm{sech}(\frac{t}{\sigma});$$

5) the Lorentzian pulse (fig. 2, f):

$$E_{in}(t) = 1/[1 + (\frac{t}{\sigma})^2];$$

6) the ultra-short pulse with sinc envelop (fig. 2,g):

$$E_{in}(t) = \sin[N_i(t/\sigma)]/[N_i(t/\sigma)]$$

(Where parameters N_i and σ denote the pulse duration);

7) For the exponential pulse (fig. 2, h):

$$E_{in}(t) = e^{\frac{t}{\sigma_1}}\theta(-t) + e^{-\frac{t}{\sigma_2}}\theta(t).$$

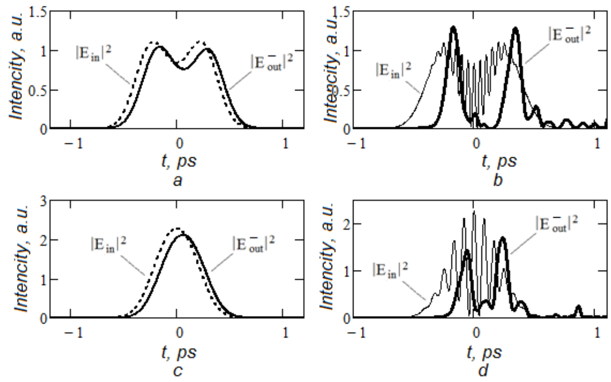

Fig. 5. Two Gaussian pulses' envelops reflected from two band-stop filters (each pulse's width is $\sigma = 0{,}2$ **ps; the temporal interval between pulses centers makes up: (a, b) - 0,5 ps; (c, d) - 0,3 ps). Droping pulses are unchirped (a, c); the same droping pulses are chirped: (b, d) (** $C = -10$ **)**

Presented structures allow manipulating the pulses' duration by changing carrying frequency (fig. 2, d; fig. 3). The figure 3 shows the magnitudes of the time delay depending on the carrying frequencies for the rectangular and Gaussian pulses. It is obvious that the change in Gaussian pulses shapes is slight.

Mutual influence of a few pulses scattered on two band-stop filters are shown in figure 4. This result demonstrates well distinguished pulses after scattering.

Preliminarily chirped pulses can be good separated too after scattering on band-stop filters systems, even if these pulses were indistinguishable before.

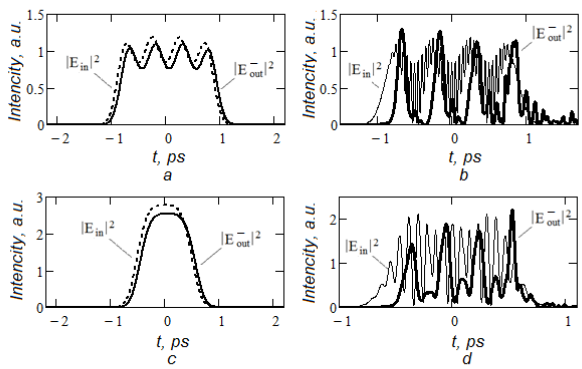

Fig. 6. Four Gaussian pulse envelops reflected from two band-stop filters (the pulses' width is $\sigma = 0{,}2$ **ps; temporal intervals between pulses' centers are: (a, b) - 0,5 ps; (c, d) - 0,3 ps). The incident pulses are unchirped (a, c); and chirped: (b, d)**

Fig. 5 shows two types of the scattering of the indistinguishable pulses, namely without and with chirping. The same result was obtained for four pulses. As it can be seen from fig. 6 the pulses are well distinguished. Eventually the scattered pulses are narrower as compared with incident.

The pulses, prepared in a special manner, even having coinciding envelopes, can be separated, if they have different frequency carriers. Let a pulse of complicated form, namely:

$$E_{\text{in}}(t) = \frac{1}{\sigma} e^{-\frac{1}{2}\cdot(\frac{t}{\sigma})^2} \sum_{n=1}^{N} \sin \Omega_n t \qquad (5)$$

is falling on N band-stop filters, where $\Omega_n = \omega_{0n} = 2\pi f_{0n}$ is the central frequency of the n-th filter.

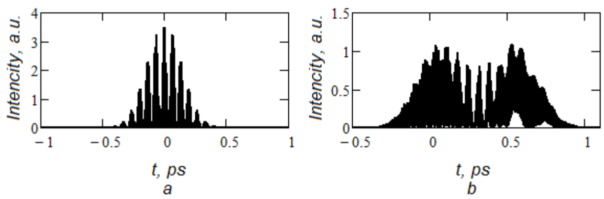

Fig. 7. Incident Gaussian pulse with two carriers (a). Gaussian pulses' intensities after scattering on two filters (b)

Figure 7, 8 shows the separation ability of the several pulses (5) after scattering. As opposed to chirped pulses' reflection, the appearance of interference impedes their differentiation that can be seen at the fig. 6, b, d.

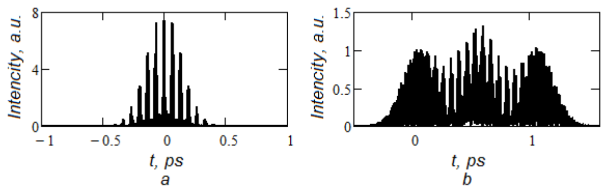

Fig. 8. Three Gaussian pulses with coincident envelops (a). Intensities of the pulses (a) after their scattering on three filters (b)

Hence, the pulses can be separated in time (fig. 7, 8, b) scattered toward source direction from band-stop filters, distributed in space by the transmission line (fig. 1, a) as in a case of two gratings.

Conclusions

By using a sequentially allocated in the transmission line band-stop filter systems with nonoverlapping frequency bands the management of optical pulses' parameters , namely: delay, separation and compression, can be provided. In contrast to 2-d and 3-d structures, the proposed devices can be easier realized in optical integral circuits in the form of quasi-one-dimensional structures.

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Розсіювання оптичних імпульсів на декількох режекторних фільтрах

Наведено результати досліджень обвідних оптичних імпульсів що розсіваються на декількох режекторних фільтрах розташованих послідовно у оптичної лінії передавання.

Розглянуто можливість стиснення імпульсів. Запропоновано нові способи розділення нерозрізненних імпульсів за допомогою їх перетворення в імпульси розрізненні за амплітудами, або у часі. Бібл. 8, рис. 8.

Ключові слова: *режекторний фільтр, мікрорезонатор, Гаусівськії оптичний імпульс, супергаусівсь-кий імпульс, прямокутний імпульс, солітоноподібний імпульс, sinc імпульс, лоренцівськії імпульс, експоненціальний імпульс.*

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Рассеяние оптических импульсов на нескольких режекторных фильтрах

Приведены результаты исследований огибающих оптических импульсов, рассеиваемых несколькими режекторными фильтрами, расположенными последовательно в оптической линии передачи.

Рассмотрена возможность сжатия импульсов. Предложены новые способы разделения неразличимых импульсов с помощью их преобразования в импульсы, различаемые по амплитудам, или по времени. Бібл. 8, рис. 8.

Ключевые слова: *режекторный фильтр, микрорезонатор, Гауссовский оптический импульс, супергаусовский импульс, прямоугольный импульс, солитоноподобный импульс, sinc импульс, лоренцевский импульс, экспоненциальный импульс.*

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