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Effect of optical filtering on pulses generated with a gain-switched DFB laser

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Abstract

Gain-switched laser diodes are widely used to generate short optical pulses, which find several applications in optical fiber measurements and high-speed optical communication systems. Temporal and spectral properties of the gain-switched pulses can be tailored by filtering their optical spectrum. Optical filtering leads to suppression of frequency chirp and generation of transform-limited pulses. We show that tuning of the center frequency of an optical bandpass filter can result in not only pulse compression, but also in the generation of a series of secondary oscillations after the primary pulse. The origin of these secondary oscillations is investigated both experimentally and analytically. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Short optical pulses have found many applications in measurements of nonlinear effects in optical fibers, optical soliton transmission, and high-speed optical time-division multiplexing (OTDM) communication systems. Several techniques have been proposed to generate short optical pulses. Mode-locked fiber-ring lasers can easily produce ultra-short optical pulses. The repetition rate of such lasers is, however, limited to values that are an integer multiple of the resonance frequency of the fiber loop. This in turn may restrict the applications of mode-locked fiber lasers in such telecommunication networks in which a variable repetition rate is desirable. Another method commonly used to produce short pulses is gain switching. To achieve gain switching, a semiconductor laser is biased below its threshold current and, subsequently, modulated with a reasonably high-voltage signal. By appropriately selecting the DC bias and the driving current of the RF signal, the laser can generate optical pulses with the duration of a few tens of picoseconds.

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Usually, the gain-switched pulses are strongly chirped, indicating that the frequency of the light varies over the duration of the pulse. This feature can be used for pulse compression using either a normally dispersive fiber or an optical filter [1–4]. In general, an optical filter is applied to remove the highly chirped pulse components, which leads to the generation of nearly transform-limited pulses. The use of optical filtering permits compact optical transmitter implementation.

In this paper, we report the effects of optical filtering on the shape of short optical pulses generated with a gain-switched distributed feedback (DFB) laser diode. We found that tuning of an optical bandpass filter over the optical spectrum of such a laser exhibits a strong effect on the temporal shape of the resulting gain-switched pulses. We also observed the generation of a series of secondary oscillations when the center frequency of the optical filter was tuned to the short-wavelength side of the spectrum. To our knowledge, this phenomenon has not yet been described in the existing works related to optical filtering of gain-switched pulses [1–4]. An investigation of this phenomenon is carried out by means of experimental observations. Furthermore, an analytical model based on filtering of linearly chirped Gaussian pulses with a Fabry–Perot filter is developed to reveal the origin of the generation of the secondary oscillations. We also give general guidelines for using a Fabry–Perot filter in tailoring of the pulse shape and spectrum for practical applications.

2. Experimental setup

In our experiments, we used a conventional RF-modulation scheme to achieve gain switching. The experimental setup is outlined in Fig. 1. A single-mode DFB-laser (Lucent 2500-series) operating at a wavelength around 1554 nm was biased with a current of $I_b = 4$ mA, which is below the threshold value of $I_{th} = 8$ mA. The sinewave signal from an RF-signal generator was amplified to an appropriate level before it was used to drive the DFB laser. A thermo-electric cooler is included in the laser package for controlling the temperature of the laser chip. The temperature of the laser was tuned to a value slightly below the room temperature. The generated optical pulses were then fed through an optical filter. We used two different Fabry–Perot filters to study the possible effects of the filter parameters on the shape of the short optical pulses. The first filter (filter 1) has a free spectral range (FSR) of 110 GHz (0.88 nm) and a −3-dB bandwidth of ≈14 GHz (0.11 nm) at wavelengths near 1554 nm. We have recently applied this filter to a directly modulated laser to reduce dispersion effects in an optical communication link [5]. The filter was fabricated from silicon and its center frequency is tunable with temperature. The second filter (filter 2) is a commercial product from Coretek having a FSR and bandwidth of ≈19 THz (150 nm) and ≈8 GHz (0.06 nm), respectively. This filter can be tuned with voltage. The pulses after the filter were amplified with an erbium-doped fiber amplifier (EDFA) in order to get a reasonable level of optical power to the photodetector (New Focus 1011, bandwidth $B = 45$ GHz). The output of the photodetector was fed to a fast digital sampling oscilloscope ($B = 50$ GHz) for measurements of the pulse shape. The oscilloscope was synchronized with the RF-signal generator. A 1×2 optical splitter was then used to couple half of the optical power (at the output of the EDFA) to an optical spectrum analyzer for measurements of the optical spectrum of the signal.

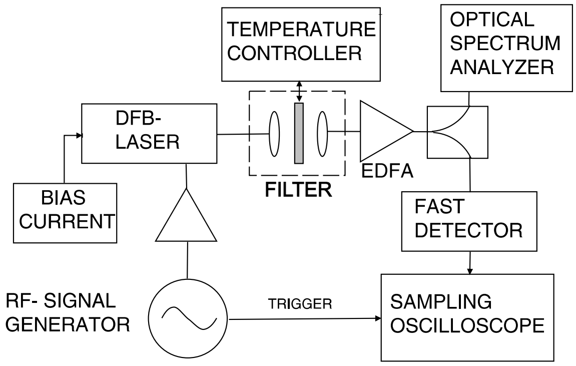


Fig. 1. Experimental setup for generating gain-switched pulses with a DFB laser and for detection of these pulses.

3. Measurement results

In the experiments, we performed several measurements of the temporal and spectral shapes of the gain-switched pulses with and without passing through the optical filter. The shape of the unfiltered spectrum indicates that the gain-switched pulses are strongly chirped [6,7]. The passband of the filter was tuned over the optical spectrum of the gain-switched laser. The optical spectra of the laser with and without filter 1 are shown in Fig. 2a, where the solid line represents the spectrum of the laser without filtering. The center frequency of the filter passband, v_0, was tuned to a few constant wavelength values within the laser spectrum. At each point both the spectrum and the corresponding time-domain waveform were measured and recorded. The reference curve, $v_0 = 0$ GHz denoted by triangles, was selected at the point where the optical spectrum was nearly symmetrical. The other positions of the center frequency of the filter were -12 GHz (squares), 12 GHz (diamonds) and 18 GHz (circles), respectively. To study the possible effect of the filter parameters on the generation of the secondary oscillations, we repeated the measurements with filter 2. The positions of the central frequency were selected close to the ones for the first filter, i.e. the shape of the spectrum is nearly symmetrical after optical filtering. The spectra of the filtered pulses are shown in Fig. 2b. The waveforms corresponding to each of the settings of the two filters are shown in Fig. 2c and d, where the pulse obtained directly from the laser is indicated with a solid line. Its leading edge exhibits a nearly Gaussian shape whereas its trailing edge has a longer tail which is a typical characteristic for gain-switched pulses. When the optical filter was applied, the shape and amplitude of the pulses were changed depending on the position of the center frequency of the bandpass filter.

By positioning the filter at the center of the signal spectrum (triangles) to produce a symmetrical spectrum, the pulse was compressed and its shape was closer to a Gaussian shape. By tuning of the center wavelength of the filter towards the longer wavelengths (squares), the optical spectrum became asymmetrical and a longer tail was generated after the trailing edge of the pulse. An interesting phenomenon was observed when the center wavelength was tuned to the short-wavelength side of the optical spectrum denoted by diamonds and circles. The pulse width decreased and at the same time a secondary oscillation appeared. The position of the primary pulse also changed in time when the central frequency of the filter was tuned over the spectrum. In general, the shape of the spectrum and the waveform of the gain-switched pulses show a similar behavior for the two filters.

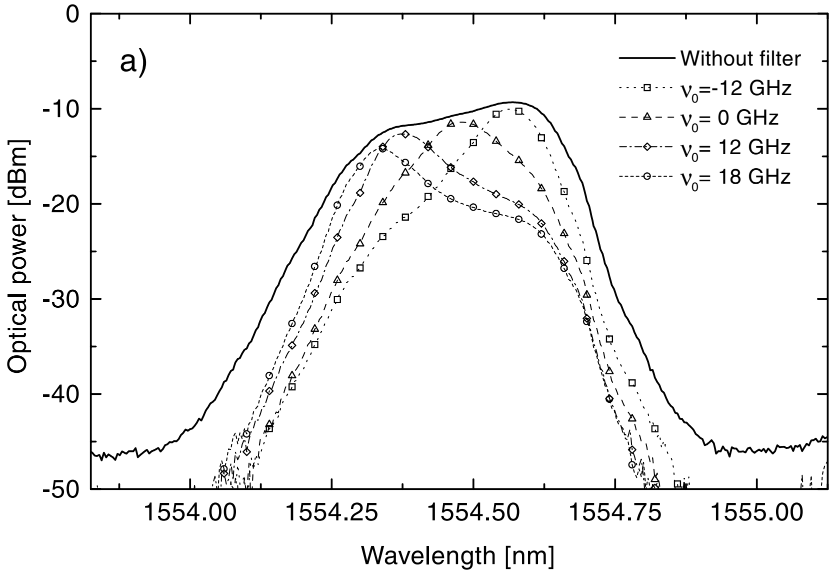
The quality of optical pulses is often described by the time–bandwidth product. Usually, it is desirable that the generated optical pulses are transform limited, which means no frequency chirp. In this case, the width of the spectrum is directly determined by the Fourier transform of the temporal shape of the pulse. For Gaussian pulses this product is given by $\Delta t \Delta f = 0.44$, where both the pulse width Δt and the spectral width Δf are given as full-width at half-maximum (FWHM) values. The measured properties of the original and the filtered signals in terms of the pulse width, the spectral width and the corresponding time–bandwidth product are summarized in Table 1.

Compared with filter 2, the use of filter 1 results in shorter pulse widths. However, the time–bandwidth product is better for filter 2 although the magnitude of the secondary oscillation compared to the primary pulse is higher. The selection of the properties of the optical filter to produce transform-limited pulses will involve a trade-off between the pulse width and the time–bandwidth product.

4. Analytical model

We conducted a study of the generation of the secondary oscillations by developing a simple analytical model. The transmission of pulses passing through a Fabry–Perot filter can be modeled by applying an impulse response, which forms an infinite series [8]. It can be expressed as

$$h(t) = (1 - R)\sum_{n=0}^{\infty} R^n \, e^{-i(2\pi v_0/\mathrm{FSR})n} \delta(t - n/\mathrm{FSR}), \tag{1}$$



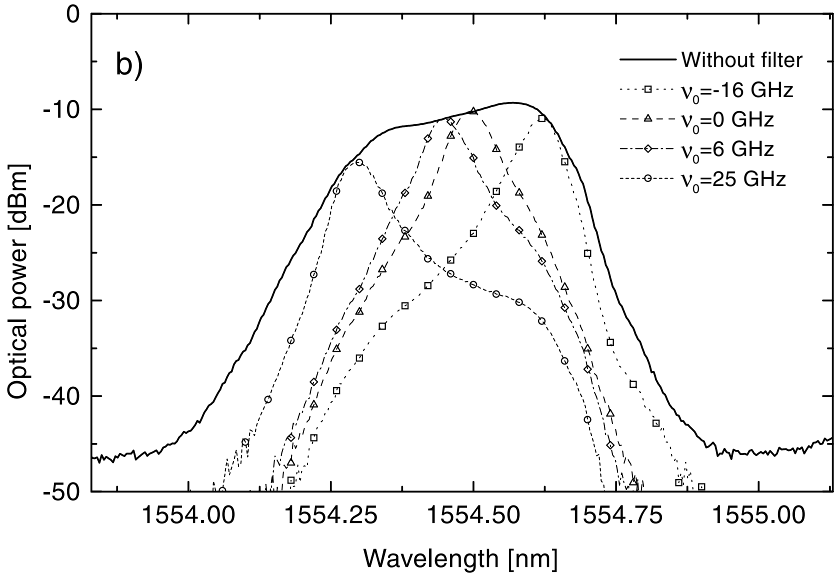


Fig. 2. (a) Measured optical spectra of the gain-switched laser filtered with the filter having a FSR of 110 GHz. (b) Optical spectra of the gain-switched laser filtered with the filter having a FSR of 19 THz. (c) Measured pulse waveforms of the gain-switched laser for several positions of the center frequency of the passband of filter 1. (d) The pulse waveforms of the gain-switched laser filtered with filter 2.

where R is the reflectivity of the mirrors, FSR is the free spectral range of the cavity, $\delta(\cdot)$ is the delta function and ν_0 represents the center frequency of a transmission fringe of the Fabry–Perot filter.

The optical signal entering the filter is modeled as a Gaussian pulse having linear frequency chirp. The electrical field of such a pulse can be written as

$$E(t) = E_0\,\mathrm{e}^{-(1/2)(t/T_0)^2}\,\mathrm{e}^{\mathrm{i}\pi Ct^2}, \qquad (2)$$

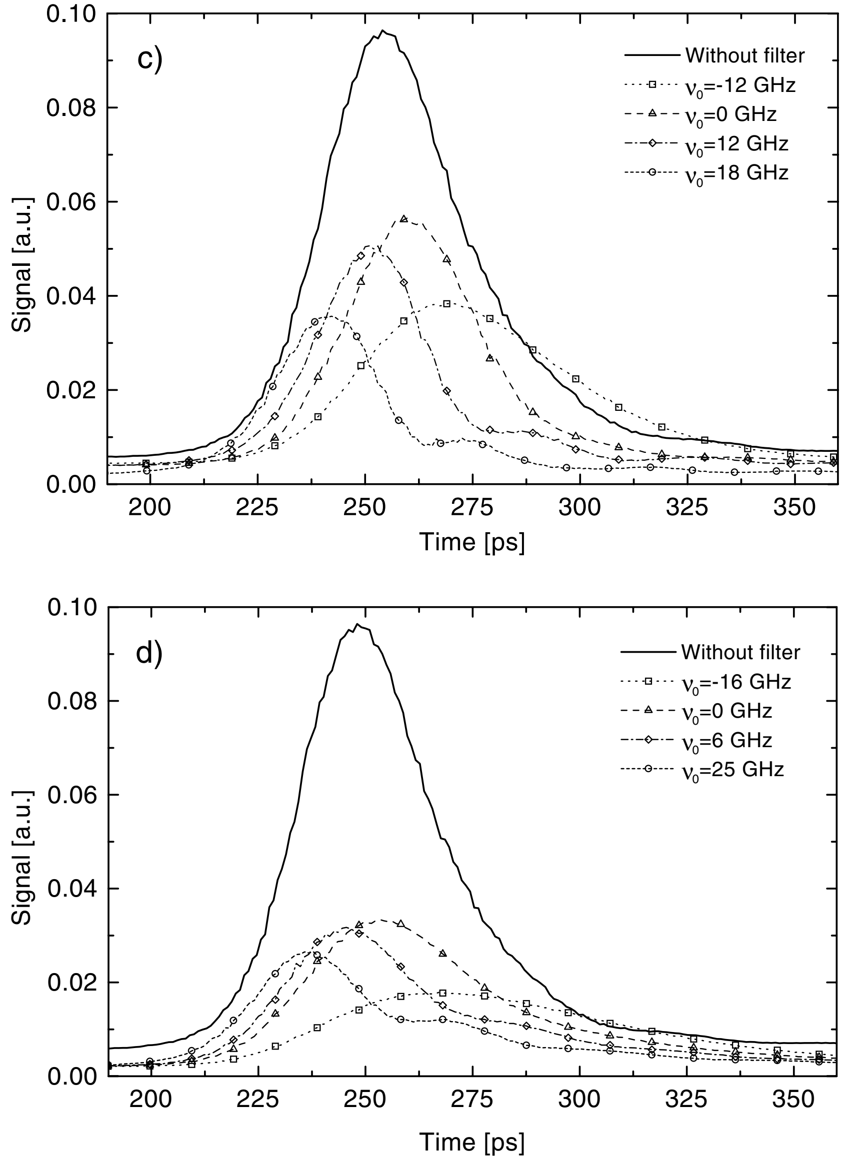


Fig. 2 *(Continued)*

where T_0 is the $1/e$-width of the pulse intensity and C is the linear chirp parameter in units of Hz/s. The spectrum of the linearly chirped Gaussian pulse is also a Gaussian function, but it is broadened compared to its transform-limited value. In the time domain, the output signal of the filter can be calculated simply as a convolution of the impulse response and the electric field of the pulses [8]. The result takes the form

$$E_{\mathrm{OUT}}(t) = E_0(1-R)\sum_{n=0}^{\infty} R^n \, \mathrm{e}^{-\mathrm{i}(2\pi\nu_0/\mathrm{FSR})n} \times \mathrm{e}^{-(1/2T_0^2)(t-(n/\mathrm{FSR}))^2} \, \mathrm{e}^{\mathrm{i}\pi C(t-(n/\mathrm{FSR}))^2}. \qquad (3)$$

Table 1
The temporal and spectral properties of gain-switched pulses with and without filtering

ν_0 (GHz)	Δt (ps)	Δf (GHz)	$\Delta t \Delta f$
Without filter	39	39	1.52
Filter 1			
−12	60	15	0.9
0	37	19	0.70
12*	31	15	0.47
18*	29	16	0.46
Filter 2			
−16	86	9	0.77
0	51	9	0.46
6*	39	9	0.35
25*	34	10	0.34

Secondary oscillations were observed for the filter positions marked by an asterisk.

The intensity of the output pulse is given as the square of the absolute magnitude of the electric field. The following observations can be made from Eq. (3) about the general features of the output pulses. The output intensity builds up from a sum of Gaussian pulses that are separated in time by the round-trip time of the cavity, i.e. $\tau = 1/\mathrm{FSR}$. The magnitude of the pulse decreases by an amount equal to the mirror reflectivity R after each round trip. The phases of the electrical fields of the pulses are affected by both the frequency chirp of the input pulse and by the selected position of the particular transmission fringe (ν_0) of the filter. The change in the shape of the output pulse is related to the interference between the sequence of pulses circulating inside the cavity.

To calculate the pulse shape we used the parameter values of filter 1, e.g. FSR = 110 GHz and $R = 0.66$. The FWHM value of the input pulse was 39 ps and the linear chirp was set to a value of $C = -750$ MHz/ps. In practise, we used the first 30 terms in Eq. (3) to calculate the output pulses. The pulse profiles displayed in Fig. 3 with solid, dotted and dashed lines are the results for three different positions of the center frequency of the filter. To confirm the results given by the analytical model, we investigated filtering of linearly chirped Gaussian pulses using commercial simulation software [9]. The results obtained by numerical simulations are shown in Fig. 3. The agreement between the two approaches was found to be excellent.

When the center frequency was positioned in the middle of the optical spectrum ($\nu_0 = 0$ GHz, solid line) the output pulse was slightly compressed

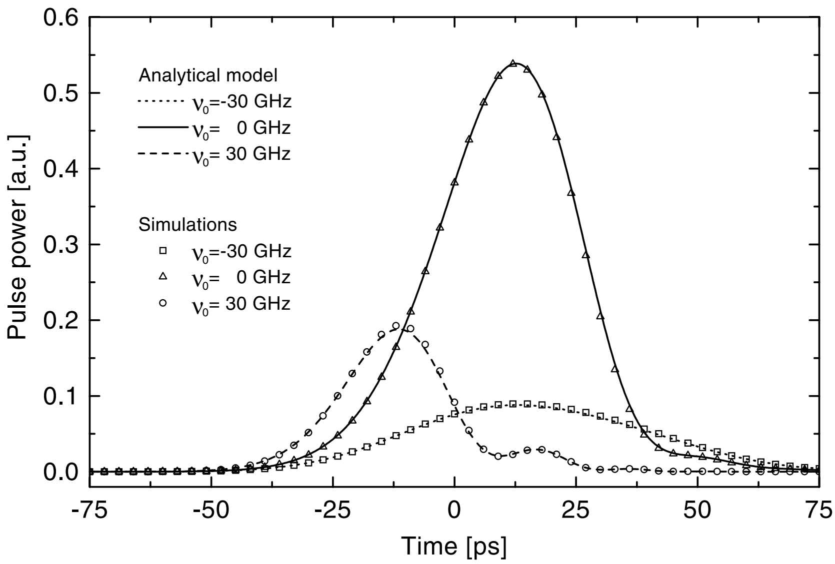


Fig. 3. Calculated intensity of the output pulses for different positions of the filter passband.

and its shape was distorted. By tuning the center frequency of the filter to higher or to lower optical frequencies by 30 GHz, the pulse will be either maximally broadened (dotted line) or compressed to its minimum temporal width (dashed line). Series of secondary oscillations following the compressed pulse were generated when the optical spectrum was asymmetrical due to the filtering and the position of the filter passband was on the high-frequency side of the spectrum. This is analogous to our experimental results, where the central wavelength of the filter was tuned to the short-wavelength side of the spectrum. In general, the features of the pulses calculated with the model are qualitatively in good agreement with the observations made in our experiments. The generation of the secondary oscillation, the temporal shift of the position of the primary pulse, and both the broadening and the compression of the pulse are consistent with our calculations. However, the model does not give accurate values for the amplitudes of the pulses for the different settings of the center frequency of the filter and the magnitude of the secondary oscillation related to the height of the primary pulse. We believe that this is due to asymmetry of the optical spectrum of the gain-switched laser resulting from the fact that the frequency chirp is not necessarily linear in real pulses [6,7].

5. Discussion

In this paper, we have studied the properties of gain-switched laser pulses optically filtered with a Fabry–Perot filter. The main effect of the filter is the reduction of the spectral bandwidth and thus suppression of frequency chirp. As a consequence, the waveform of the gain-switched pulses was also changed. When the center frequency of the filter was tuned to make the spectrum of the optical pulse symmetrical, then also the waveform of the pulse became more symmetrical and nearly Gaussian. The pulse can be further compressed by tuning the center frequency of the filter to the short-wavelength side of the spectrum. However, in this case also a series of secondary oscillations appeared. The origin of the generation of these oscillations was investigated with an analytical model based on filtering of linearly chirped Gaussian pulses with a Fabry–Perot filter. The relationship of the optical phases among the output pulses after several round-trips inside the Fabry–Perot cavity were identified to be the main source of pulse broadening and the generation of the secondary oscillations.

In conclusion, our results indicate that the position of the filter needs to be carefully selected in order to avoid the generation of secondary oscillations. These oscillations may cause intersymbol interference in high-speed optical communication systems leading to degradation of the transmission performance.

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