High-speed optical pulse train generation based on line-by-line spectral intensity coding

Zhang Jia, Kim Ik-Hwan, Hong Sang-Jeen and Seo Dong-Sun

Department of Electronics, Myongji University, San 38-2, Nandong, Cheoin-gu, Yongin, Gyeongido 449-728, Korea
E-mail: sdsphoto@mju.ac.kr

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Abstract. We have built a simple line-by-line spectral intensity coder with 4 GHz resolution at 1.55 μm using a grating, a collimating lens, and an intensity mask. By applying a 10 GHz mode-locked spectral comb to the coder, we have generated relatively stable 20 – 100 GHz pulse trains with 10 GHz steps. The characteristics of generated pulse trains are examined quantitatively by measuring the corresponding optical spectra, time-domain waveforms, autocorrelation traces, and radio-frequency spectra.

Keywords: optical pulses, spectral intensity coding, repetition rate multiplication, pulse shaping

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1. Introduction

Optical processing based on individual spectral line control of a mode-locked laser, which is named as “line-by-line pulse shaping”, is very attractive for arbitrary waveform generation, optical CDMA (code division multiple access), microwave photonics, etc. [1–3]. Simple examples of applications of the line-by-line pulse shaping are spectral intensity coding or filtering of low-speed mode-locked lasers for repetition rate multiplication. When compared with other repetition-rate multiplication methods, spectral filtering is inherently simple. We have earlier studied a simple spectral filtering of a mode-locked spectral comb using a high-finesse Fabry–Perot etalon filter and have successfully generated 40 GHz and 100 GHz pulse trains from a 10 GHz mode-locked laser [4]. One of imaginable disadvantages of the etalon filtering method is a lack of flexibility. At the same time, the method to be suggested in the present work is simple like the spectral filtering scheme used in the study [4] and, in addition, reveals much greater flexibility.

A simple line-by-line spectral intensity coder built here is based on a reflective geometry [5].

For simplicity we have employed a single fibre-pigtailed collimator, removing an additional large beam expander used in Ref. [6], though we can still achieve high enough resolution for the line-by-line spectral coding of a 10 GHz spectral comb. In addition, we have used a low-cost mask for spectral intensity coding, instead of expensive liquid-crystal modulator arrays used in the other works [5–7]. The two-dimensional pattern of the intensity mask has enabled us to select different sets of slits of which spacing is determined by the spectral position of a repetition-rate multiplied pulse train. In this way the scheme suggested can have reasonably good performance and more practical flexibility than the other spectral filtering configurations, e.g. the etalon filtering. Note that the scheme based on a fixed mask is much simpler than a similar scheme based on liquid-crystal modulator arrays [6].

2. Experimental setup

Our experiment setup is shown in Fig. 1. A 10 GHz spectral comb generated from a mode-locked fibre laser is spectrally coded (for filtering) by a spectral line-by-line intensity coder. The coded output is amplified and measured by an optical spectrum analyser (a 0.07 nm resolution), an intensity autocorrelator, a 40 GHz sampling scope, and a RF spectrum analyser (0–25 GHz) coupled with a 26 GHz photodetector.

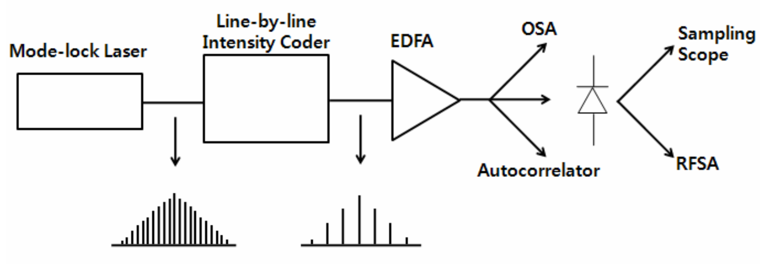


Fig. 1. Experiment setup (EDFA means erbium-doped fibre amplifier, OSA an optical spectrum analyser, and RFSA a radio-frequency spectrum analyser).

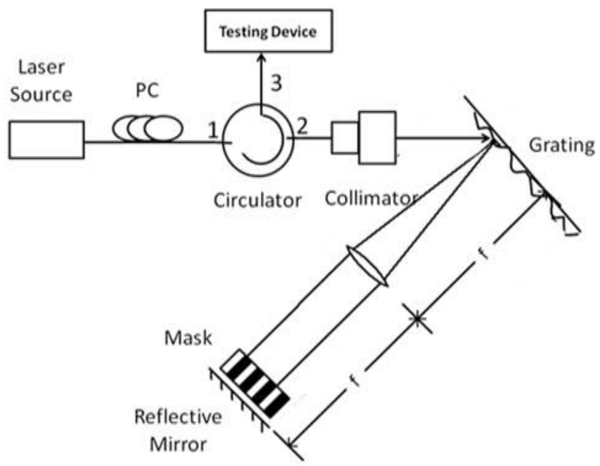


Fig. 2. Schematic diagram of our reflective line-by-line intensity coder (PC is a polarisation controller).

Fig. 2 shows a schematic diagram of line-by-line intensity coder suggested by us, in which a fibre-coupled Fourier-transform pulse shaper is constructed in a reflective geometry. A fibre-pigtailed collimator expands the input beam to the size of ~ 9 mm on a 1100 grooves/mm grating, in order to enhance the coder resolution. Discrete spectral lines of a mode-locked laser are diffracted by the grating and focused by a lens with 50-mm focal length. A polarisation controller (PC in Fig. 2) is used to adjust for horizontal polarisation on the grating. A two-dimensional intensity mask of slits with different slit spacings is placed in the focal plane of lens to pass or block individual spectral lines. Details of split spacing and/or mask design will be discussed later.

Fig. 3 shows schematically a two-dimensional mask pattern and transmitted optical comb spectra corresponding to the individual slits. Here white bars represent the transparent slits and black parts correspond to the opaque regions. Due to Fourier-transforming properties of combination of the grating and the lens, the individual mode-locked spectral comb lines line up horizontally in a row of the mask. By moving the mask vertically, we can select a specific slit pattern for spectral intensity coding. For example, if the first row is selected, all of the spectral lines would pass through the mask. When the second column is selected, some other spectral lines would pass. This results in the spectral spacing of the passed signal becoming exactly twice the input spacing. The latter means that the pulse repetition rate given by inverted spectral spacing is twice as large as the input one. In this way our simple mask enables line-by-line spectral intensity control over an entire optical band for various rates of repetition multiplication. A retro-reflecting mirror provides double-pass geometry and all of the spectral lines transmitted through the mask are recombined into a single fibre and separated from the input via an optical circulator. The total loss inserted by an input circulator port 1 to an output port 3 is about 8.5 dB. In view of the insertion loss, a weak signal should be amplified by an er-

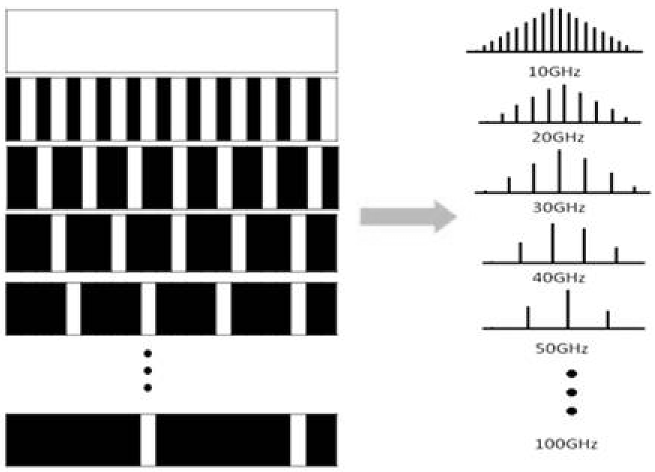


Fig. 3. Schemes of two-dimensional mask pattern (left) and transmitted optical comb spectra (right).

bium-doped fibre amplifier (EDFA in Fig. 1) for easy measurements of its characteristics, such as autocorrelation traces.

Basing on the Fourier transforming property of the spectral coder shown in Fig. 2, one can get a relationship between the wavelength difference ($\Delta\lambda$) and the spectral line spacing (Δx) at the focal (or mask) plane for the first-order diffraction at the grating. Assuming that the horizontal direction at the mask plane is given by x axis, one arrives at the following spectral slope ($\Delta\lambda/\Delta x$) at the mask plane:

$$\frac{\Delta\lambda}{\Delta x} = \frac{d\cos\theta_d}{f}, \quad (1)$$

where d is the grating constant, θ_d the diffraction angle, and f the focal length of the lens. For the grating of 1100 grooves/mm, the lens of 50 mm focal length, and the diffraction angle of 52°, the spacing between the 10 GHz (0.08 nm at 1.55 μm) spectral lines at the mask plane becomes 72 μm. Based on this value, we can fix the width and/or the spacing of the mask pattern slits, as shown in Fig. 3.

3. Spectral resolution and mask pattern design

Now we obtain the beam radius w_o at the mask plane,

$$w_0 = \frac{\lambda f \cos\theta_i}{\pi w_i \cos\theta_d}, \quad (2)$$

where λ is the light wavelength, θ_i the angle of incidence at the grating, and w_i the incident beam radius. We define the beam diameter, $2w_0$, as a spectral resolution of the coder.

With our experimental parameters ($\lambda = 1.55$ μm, $w_i = 9$ mm, $f = 50$ cm, $\theta_d = 52°$, and $\theta_i = 66°$) we get the beam diameter $2w_0$ equal to 37 μm. From the relationship given by Eq. (1), we then obtain the spectral resolution of 5.2 GHz. Notice that the above resolution is still insufficient for controlling individual 10 GHz spectral lines.

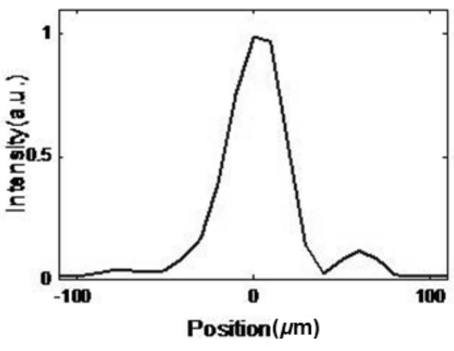
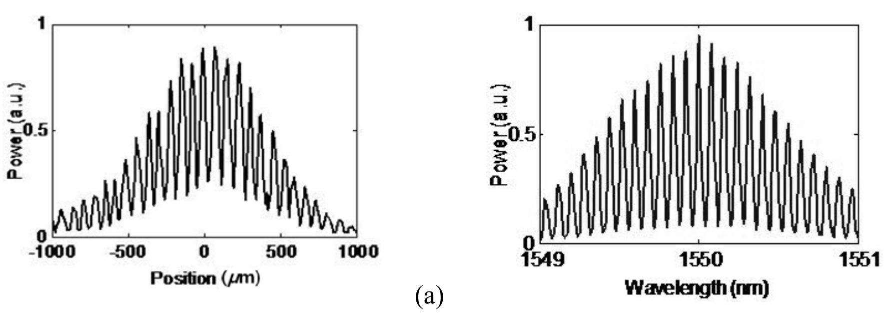


Fig. 4. Intensity distribution at the mask plane obtained for a monochromatic input of the coder.

In order to confirm the resolution and the spacing between 10 GHz spectral lines calculated here, a bare fibre tip coupled with an optical power meter has been placed at the mask plane (see Fig. 2). The output power coupled into the fibre tip has been recorded as a function of horizontal translation (along the z axis). To find the spectral resolution, we have injected monochromatic light into the coder and measured the intensity distribution at the mask plane, as shown in Fig. 4. The beam width measured at a $1/e^2$ power point is ~ 50 µm, thus corresponding to the spectral resolution of ~ 7 GHz. As we think, the beam width larger than its calculated value originates mainly from the resolution of the measuring system (~ 10 µm) and possible errors of the alignment.

Now we replace the monochromatic source by a 10 GHz mode-locked comb source and perform similar measurements. Fig. 5 shows the results, which confirm that the spacing between the 10 GHz spectral lines is ~ 72 µm. This spacing agrees well with the calculated one. To check the accuracy of our system, the input optical spectrum measured by the optical spectrum analyser (Anritsu Model MS9710B; the resolution of 0.07 nm) has been mapped onto the figure (red line). The both traces are well agreed in shapes, showing that the spectral comb lines are ready to be coded by a given mask pattern.



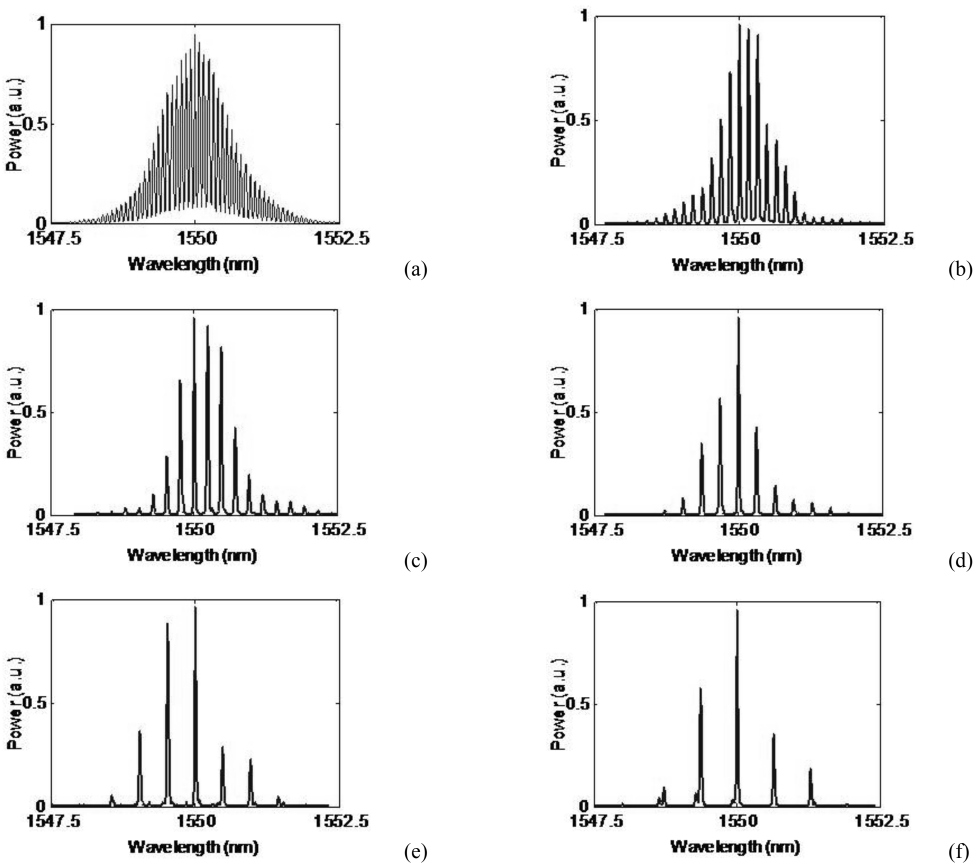
(a) (b)

Fig. 5. Intensity distribution measured at the mask plane when a mode-locked comb source is applied at the coder input (a). For the sake of comparison, figure (b) shows the corresponding input spectrum measured by the optical spectrum analyser.

Basing on the experimental measurements, we can fix the detailed dimensions of the mask pattern shown schematically in Fig. 3. The width of 72 µm for the transparent slits is sufficient to pass on almost all the power from a given spectral line and block any power from the unwanted spectral lines. The spacing between the slits is an integer multiple of 72 µm (i.e., the spacing between the fundamental 10 GHz spectral lines), as shown schematically in Fig. 3. Here the integer is determined by the pulse repetition rate factor intended. For instance, it becomes twice 72 µm for the 20 GHz train, three times larger than 72 µm for the 30 GHz train, and so on.

4. Experimental results and discussions

As we have already mentioned, a mode-locked laser output of 10 GHz is characterised by evenly spaced discrete spectral lines (an optical frequency comb) with the frequency spacing equal to the pulse repetition rate at 10 GHz. The intensity mask in the Fourier-transform plane of the line-by-line intensity coder transmits the spectral lines among the 10 GHz comb which are coincide with the transparent slits and it blocks (i.e., filters out) the unwanted spectral components which fall into the opaque regions. This simple spectral filtering of the 10 GHz spectral comb generates a new spectral comb with the spacing of an arbitrary integer multiple of 10 GHz. Even if careful adjustment for matching the spectral line positions and the mask slits is required, we can get reasonably good results (see some of them in Fig. 6). Fig. 6 proves successful generation of repetition-rate multiplied pulse trains (from 20 GHz to 100 GHz, with a 10 GHz step) using spectral filtering by the coder. A slight deformation of the transmitted spectrum and some residual power in the removed spectral components are observed due to mask-patterning errors and misalignment between the spectral comb and the mask slits. A similarity of the spectral envelopes observed on the input and output confirms that the individual pulse shapes remain almost same after the repetition rate multiplication.



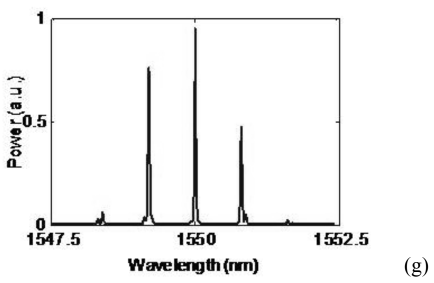
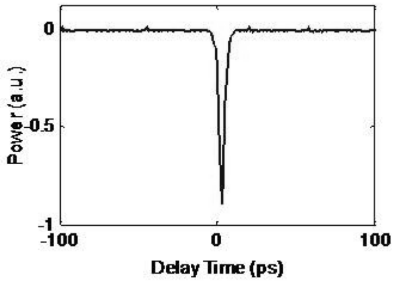
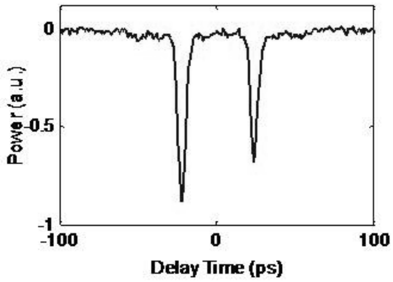


Fig. 6. 10 GHz input (a) and filtered output optical spectra, showing repetition-rate multiplied pulse trains at 20 GHz (b), 30 GHz (c), 40 GHz (d), 60 GHz (e), 80 GHz (f), and 100 GHz (g).

To inspect quality of the pulse trains generated, we have measured the autocorrelation traces of the filtered outputs (see Fig. 7). As expected, the pulse period is reduced from 100 ps to 50, 33.3, 25, 16.7, 12.5 and 10 ps, respectively. The traces also testify that both the input and output pulse widths are almost same, as expected for the spectra envelopes shown in Fig. 6. In this way we can reconfirm that the pulse trains from 20 GHz to 100 GHz are successfully generated from the 10 GHz comb source, owing to simple spectral filtering based on our line-by-line spectral intensity coder.



(a)



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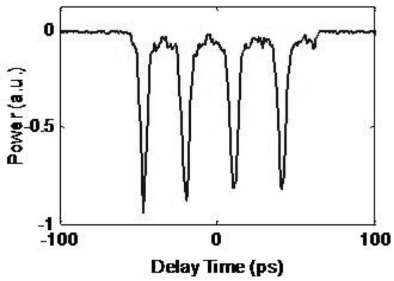
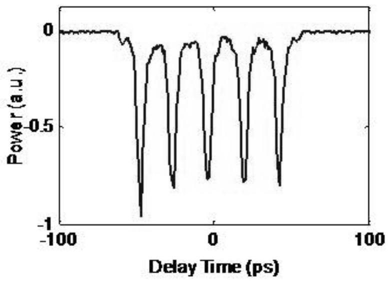
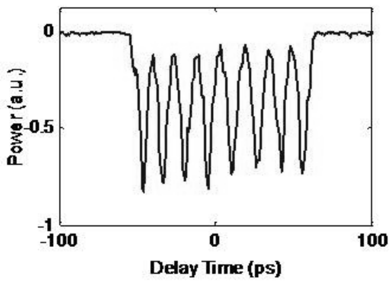


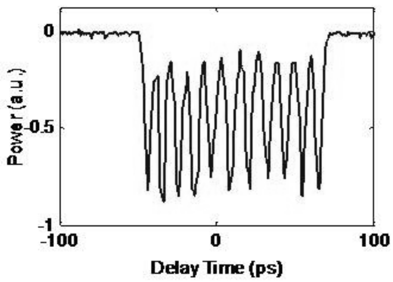
(c)



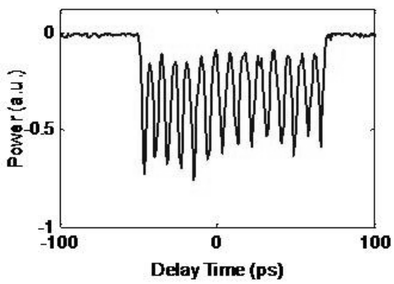
(d)



(e)



(f)



(g)

Fig. 7. Autocorrelation traces for (a) 10 GHz (input), (b) 20 GHz, (c) 30 GHz, (d) 40 GHz, (e) 60 GHz, (f) 80 GHz, and (g) 100 GHz trains.

Finally, we have measured directly the time traces for the 10 GHz input and the outputs ranging from 20 GHz to 40 GHz, using a 40 GHz fast sampling scope (see Fig. 8). Again, reasonably stable 20, 30 and 40 GHz pulse train generations are confirmed. We believe that a slight envelope modulation present at 10 GHz comes from residual spectral components and a spectral envelope distortion shown in Fig. 5.

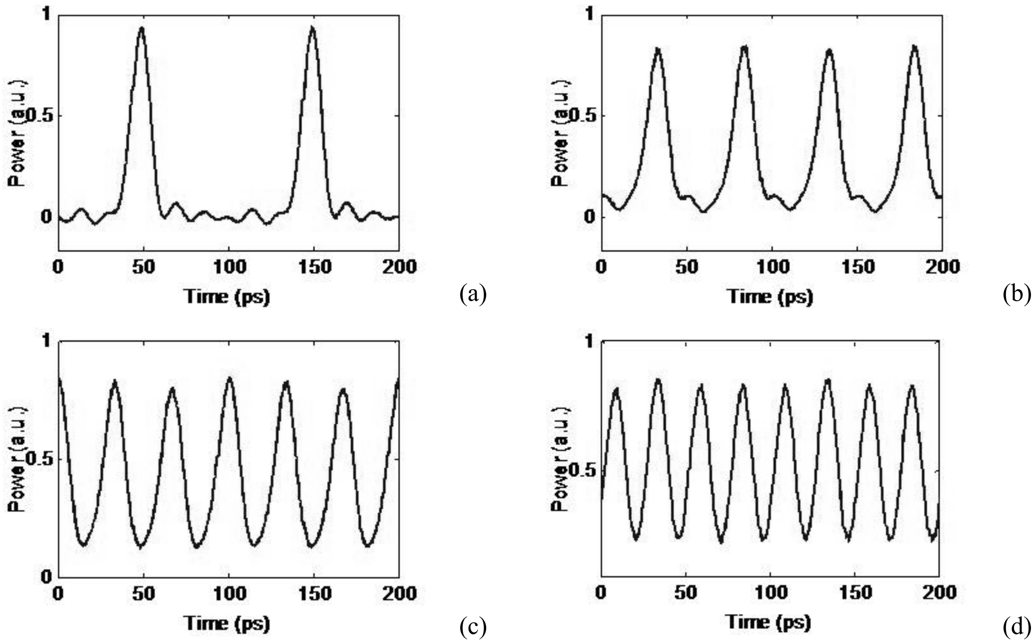
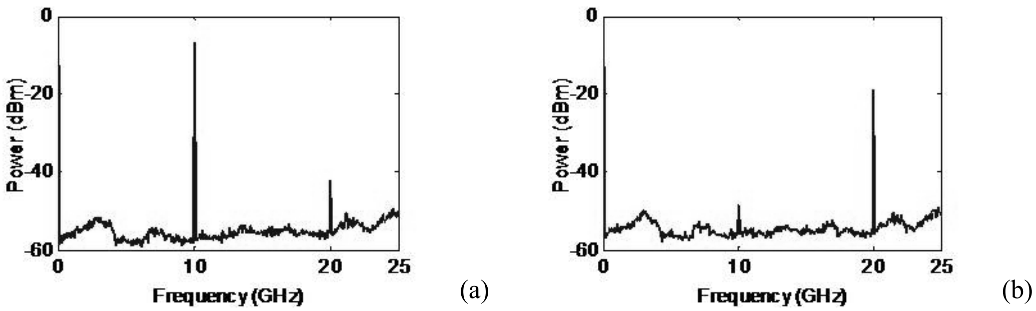


Fig. 8. Sampling scope traces for (a) 10 GHz (input), (b) 20 GHz, (c) 30 GHz, and (d) 40 GHz pulse trains.



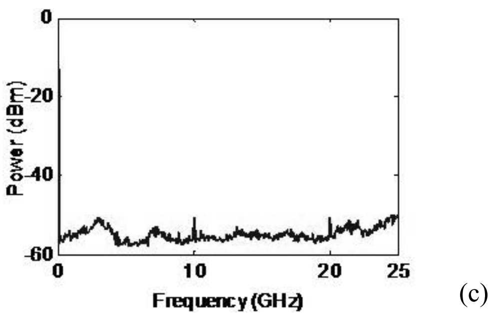


Fig. 9. RF spectra measured for (a) 10 GHz, (b) 20 GHz, and (c) 30 GHz trains.

For checking the amount of the residual 10 GHz component in the repetition-rate multiplied waveforms depicted in Fig. 8, we have detected the pulse trains with a fast detector and examined their radio-frequency spectra. For a comparison, we have kept almost the same optical power level at ~ 0 dBm for each waveform (Fig. 9). Here, the radio-frequency spectrum has been measured up to 25 GHz, the limit of our measurement facilities. The 10 GHz input pulses show a clear 10 GHz component and its second harmonic, as shown in Fig. 9a. For the 20 GHz train, the 10 GHz component is negligible (~ 28 dB lower than the 20 GHz signal – see Fig. 9b). The levels of suppression for the 10 and 20 GHz components in the generated 30 GHz pulse trains are similar (see Fig. 9c). The fact of sufficient suppression of the 10 GHz component in both the 20 and 30 GHz trains proves a stable repetition-rate multiplied pulse train generation.

5. Conclusion

We have built a simple and cost-effective line-by-line spectral intensity coder with the resolution of ~ 7 GHz at 1.55 μm. It utilises a grating, a collimating lens, an intensity mask, and a retro-reflection mirror. Basing on spectral filtering capability of this spectral intensity coder, we have experimentally generated multiple tens-of-GHz pulse trains at 20 – 100 GHz (with the 10 GHz step) from a mode-locked 10 GHz laser. For spectral filtering, a simple and easily made intensity mask has been employed, which is placed in the Fourier-transform plane of our intensity coder. The quality of the high-speed pulse trains generated has been examined by measuring the optical spectra and the autocorrelation traces. Both the measurements have proved successful generation of the repetition-multiplied pulse trains, showing good suppression of the unwanted spectral lines and clear dips between the pulses seen in the autocorrelation traces. However, there has been a slight mismatch between the spectral line positions and the mask patterns that lead to some spectral envelope distortion and unwanted residual power of the transmitted signal spectra. The quality of the repetition-multiplied outputs has been examined in detail using the measurements of direct time traces and the corresponding radio-frequency spectra. Relatively clean sampling scope traces reconfirmed a fact of stable high-speed pulse train generation. The radio-frequency spectra have testified a suppression of 10 GHz component greater than 28 dB for both the 20 and 30 GHz pulse trains. It is also worthwhile that our technique is ready for applications when generating other high-speed pulse trains.

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Анотація. *У роботі запропоновано порівняно простий спектрально-лінійчатий кодер інтенсивності з розділенням 4 ГГц на довжині хвилі 1,55 мкм, у якому використано ґратку, колімаційну лінзу та маску інтенсивності. Для гребінчастого спектру з періодом 10 ГГц і синхронізацією мод ми генерували доволі стабільний цуґ імпульсів із кроком 10 ГГц і шириною 20 – 100 ГГц. Характеристики генерованого цуґу імпульсів досліджено шляхом вимірювання оптичних спектрів, форми сигналів, автокореляційних слідів і радіочастотних спектрів.*