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# Sampled fiber gratings for picosecond time delay signal processing

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ABSTRACT

Sampled fiber grating for high-resolution time-domain signal processing is investigated. Sampled fiber grating is useful to introduce precise time delays in picosecond (ps) across many wavelength channels. We analyze and simulate for $Sinc^2$ sampled fiber grating, and show that a large number linear sub-ps time delays can be achieved by the grating. We present that Gaussian sampled fiber gratings can be fabricated by inscribing optical fiber by Gaussian laser beam, and can realize short time delays over a number of wavelength channels with a required time delay profile. For a Gaussian sampled fiber grating fabricated, an average time delay step of 4.49 ps with 10% linearity for 8 wavelength channels, and an average delay step of 2.5 ps with 8% linearity if for 4 channels, are realized. A physical model of cascaded equivalent Fabry-Perot cavities together with rectangular truncation of the inscription laser beam for the Gaussian sampled refractive index is suggested, and used to explain the grating spectra. A technique for time delay step tunability of the grating is presented. Some issues are discussed with conclusions given. We demonstrate that the sampled fiber gratings have capability to provide a large number of picosecond time delays with good linearity. This offers a simple technique for ps-high-resolution signal processing in time-domain and THz signal generation.



## 1. Introduction

Photonic signal processing has been researching in recent decades [1–3]. While most concerns have been focused on frequency domain performance of signals such as photonic RF filters [4–6], research on time domain for signals to acquire small time interval down to 1 picosecond(ps) using photonic technique is rarely seen in publication. In this article, our investigation using sampled fiber grating to realize ps-interval multiple signal paths is reported. Previously, sampled fiber grating (SFG) has been explored for generating wavelength channels used in optical signal processing in wavelength domain such as signal multiplexing [7–9] and dispersion compensation [10,11]. However, SFG used in time-domain signal processing such as signals queuing in time, especially in requiring high-resolution with time interval of picosecond, e.g. ps-time delay lines, has not been well studied to our knowledge. Sampled fiber grating with short fiber length can create a large number of wavelength channels with inter-channel time delays in picosecond.

Optical signal time delay with ps interval is important in applications, for example microwave phased array antenna (PAA) systems. As shown in Fig. 1 for a linear PAA operating in receiving mode, when the echo wavefront arrives with a small angle at the arrayed antennas, the time delay needed for time compensation can be as small as some picoseconds. In multi-beam operation of a PAA system, with increase of number of the beams or/and increase of the operation frequency the required time delay can also be as small as 1 or several picoseconds. For example, a PAA system operating 256 beams at 2 GHz frequency needs time delay of 2 ps within the antenna elements [12]. When using a photonic method to obtain the time delays, microwave signals modulate light carriers. The later travel through a time delay line (i.e. SFG in our case) to achieve required time delays for compensation, and then arrive at photodetectors where microwave signals are recovered, and time delays of optical domain are transformed into time delays in electrical domain. This is not shown in detail in Fig. 1 for simplicity. Since optical signals with constant ps-time interval can be converted by photodetector into electrical signal with terahertz (THz) repetition rate in frequency domain, SFGs can also provide a way to generate THz signals with using broadband or multi-wavelength optical source. The later is used to illuminate the SFG wavelength channels.

Some techniques have been reported for obtaining short time delays [13–16]. Discrete fiber Bragg gratings (FBGs) or a number of optical fibers with small length differences can be arranged to

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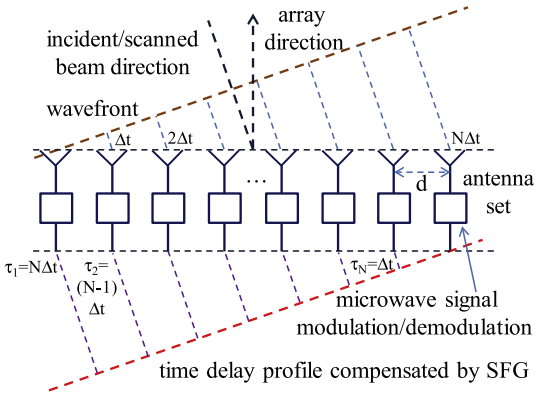


**Fig. 1.** Illustration of requirement on time delays of a PAA system. Δt, 2Δt,..., NΔt are time differences of signal arriving at antenna elements. $\tau_1$, $\tau_2$,..., $\tau_N$ are the corresponding time delays, compensated by SFGs. d is antenna element spacing.

generate time delays of several tens of ps, but difficult to reach smaller time steps due to the limitation of fiber length differences in cutting and fusion splicing operation, which is a couple of millimeters [13–14]. Chirped fiber grating can provide continuous and any time delays. Unfortunately, because of its dispersion characteristics it is not able to support broadband operation of signals [15]. Superposed FBG was investigated to realize ps-time delays [16], but it has difficulty in superposing a large number of FBGs within same fiber region in fabrication. In this report, we show a large number of linear ps-time delays obtainable by using Sinc$^2$ sampled fiber grating. Gaussian sampled fiber gratings are designed and fabricated by using Gaussian laser beam inscription, and investigated in experiment for generation of many ps time delays. A physical model of cascaded F-P cavities and truncation effect is suggested for explaining the characteristics of the grating spectra of SFGs. Some issues are discussed. Channel delay step tunability of the proposed SFG is considered with a tuning technique presented.

## 2. ps-time delays generated by SFGs

A sampled fiber grating can be expressed mathematically as:

$$\delta n_e(z) = \delta n_{e0}\sum_{n=1}^{s}\mathrm{Rect}\left[z-\left(n-\frac{1}{2}\right)L_s,\frac{L_s}{c}\right]Sampling[z]Cos(4\pi n_e z/\lambda_0) \tag{1}$$

where the three functions after the summation sign are rectangular function, sampling function, and seed grating refractive index function, respectively. The parameters $n_e$ is effective refractive index of fiber core, $\delta n_{e0}$ is amplitude of index change, $L_s$ is grating sampling period i.e. L/s where L is grating length and s is number of samples, which is defined by the width of the Rect function. The Rect function used here is for truncation of the tails of sampling function e.g. Gaussian function. s sections of truncated function joint together to form a complete sampling function. Sampling function determines the spectral profile shape of the sampled fiber grating significantly, and the Rect function modifies the profile. As well known, the spectra of a sampled fiber grating can be calculated and obtained by solving the coupled mode equations [17].

Reflectivity and time delay characteristics with coupling coefficient for fiber Bragg gratings (FBGs) have corresponding linearity in a certain range of coupling coefficient as shown in the report [19]. This can be used to consider the case of SFGs. The varying reflectivity values of wavelength channels correspond to different mode coupling coefficients of a SFG. This infers for SFGs that time delay profile linearity can be predicted from known reflectivity profile, and the later is determined by the refractive index distribution defined by Eq. (1). Therefore, according to Fourier transform, if a Sinc$^2$ function is used to make a SFG, a triangular reflectivity profile can be available from the grating, and many time delays within linear spectral profile can be obtained. A Sinc$^2$ function for the sampling is written as:

$$Sampling(z) = \sum_{n=1}^{s}\left\{Sin\left[2N_s\pi\left(\frac{z}{L_s}-n+\frac{1}{2}\right)\right]\right\}^2 \Big/ \left\{2N_s\pi\left(\frac{z}{L_s}-n+\frac{1}{2}\right)\right\}^2 \tag{2}$$

where $N_s$ is number of the sidelobes of Sinc$^2$ function. Fig. 2 shows the simulation results of a Sinc$^2$ SFG with parameters set for L = 2 cm, $n_0$ = 0.01, number of sidelobes $N_s$ = 80, and number of samples s = 10. It can be seen that the time delay profiles on both sides are very linear. An average time delay step of 0.25 ps is obtained from this SFG. All of the 39 channels on the left side and 35 channels on the right side have >99% reflectivity. This is due to the large index change of 0.01 [18] set for the grating even though the Sinc$^2$ function sidelobes are weak. In Fig. 2(b), 16 wavelength channels from 1561 nm to 1567.5 nm on the right side in Fig. 2(a) are selected to display their time delay minima. Results show that the 16 channels have a linear profile with a standard deviation of 4.2% from linear characteristics, and an average delay step of 0.25 ps. In this case, a larger number of channels can be available if linearity requirement is relaxed. On the other hand, a higher linearity can be achieved with a fewer number of channels to be considered.

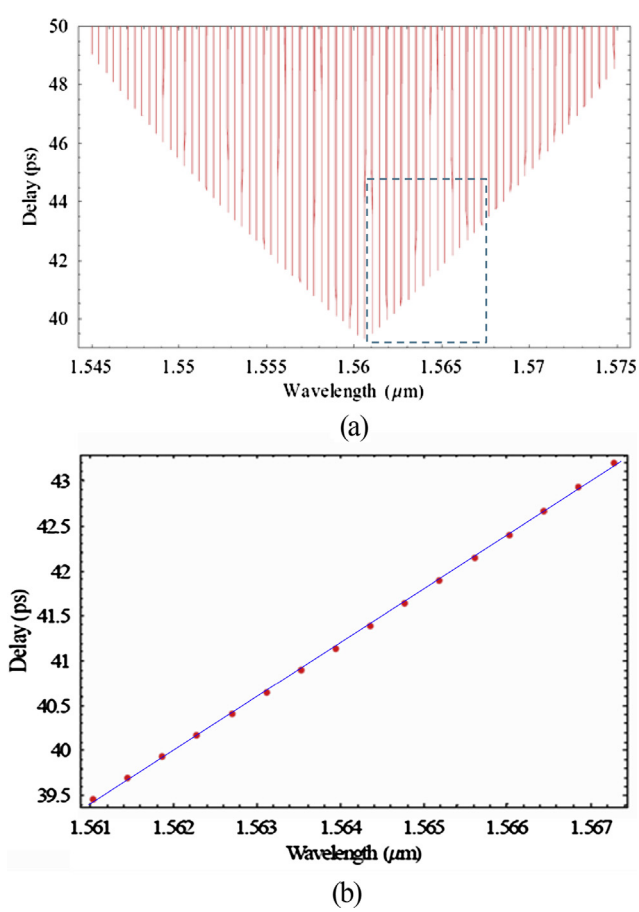


**Fig. 2.** (a). Time delay spectrum with large number of sub-ps delay steps and linear profile generated from a Sinc$^2$ sampled FBG. (b) Distribution of the time delay minima of the 16 channels selected as shown in Fig. 2(a) and the linear approximation line.