Optical frequency combs generation with collinear acousto-optic interaction

Mantsevich, Sergey, Yushkov, Konstantin, Voloshin, Andrey


Event: SPIE Photonics Europe, 2020, Online Only, France
Optical frequency combs generation with collinear acousto-optic interaction

Sergey N. Mantsevich*a, Konstantin B. Yushkovb, Andrey S. Voloshinc
aPhysics Department, M.V. Lomonosov Moscow State University, 1 Leninskie Gory, Moscow, Russia, 119991; bNational University of Science and Technology “MISIS”, 4 Leninsky Prospect, Moscow, Russia, 119049; cRussian Quantum Center, 45 Skolkovskoye shosse, Moscow, Russia, 121353

ABSTRACT

Optical frequency combs (OFC’s) are extremely important for optoelectronics to date. They have found a great variety of practical applications. Some of proposed OFC’s generation methods apply acousto-optic (AO) devices. The AO devices in such schemes are used either as the element devoted to the OFC phase stabilization or, much less often, they play the role of the key element responsible for optical radiation frequency shifting in the frequency-shifting loop (FSL). In this paper we continue the theoretical examination of new OFC generation method based on joint application of collinear AO diffraction geometry and FSL. This method gives two novel OFC generation schemes. In the first one collinear AO cell is fed by radio-frequency (RF) generator and FSL connects AO cell optical output and input. The second scheme includes not only FSL but also the optoelectronic feedback connecting the optical output of the system with the piezoelectric transducer of the AO cell. In this case the system operates like optoelectronic generator and external RF generator is not needed. The theoretical model is presented for both cases. Each of the systems gives the possibility to generate OFCs in several ways with varying characteristics. The influence of collinear AO diffraction parameters on the generated OFC characteristics such as spectral width, number of spectral components and envelope shape is examined.

Keywords: acousto-optics, collinear interaction geometry, optical frequency combs, feedback, acousto-optic mismatch

1. INTRODUCTION

The emergence of the generation of ultra-short laser pulses sequences that, from spectral point of view, have optical spectrum containing thousands of equally spaced narrow lines1 gave new opportunities for optoelectronics. Optical frequency combs (OFC’s) have found wide application in various fields of optical electronics to date2–5.

The OFC’s characteristics are defined by the method they were obtained. The first OFCs were generated with femtosecond lasers1. The spectral spacing between the components in such combs varies from 10MHz to 1GHz and is set by the laser cavity length. If higher line spacing is needed, the Kerr combs are applied. These combs are generated with nonlinear microresonators with extraordinary high Q-factor have spacing varying from 1GHz to 1THz6–10. Many new ways to generate OFC were also examined11–13.

OFC generation technique basing on consistent CW laser frequency shifting is also popular. The electro-optic (EO), acousto-optic (AO) or single-side band (SSB) modulators are inserted into the optical frequency shifting loop (FSL), in order to obtain the frequency shift of the seed laser optical radiation14–18. Both AO and EO modulators pave the way to tunable comb generator with both tunable central frequency and the comb spacing. The comb position and the span are defined by the seed CW laser wavelength and the transmission of the optical loop.

To date AO devices application in the OFC FSL generation schemes is not as popular as EO modulators. However, AO OFCs have some advantages comparing with EO combs. AO devices are relatively simpler as the EO cell for effective operation requires the application of higher voltages compared to the AO cell. AO devices give also the possibility to control the OFC envelope.

*snmantsevich@yahoo.com; phone +7 495 939 46 97

Downloaded From: https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie on 21 Apr 2020
Terms of Use: https://photonicsforenergy.spiedigitallibrary.org/terms-of-use
It was shown also that it is possible to use AO devices for high resolution multi-heterodyne spectroscopy and generation of OFCs with broad band and comparatively flat spectra\textsuperscript{19,20}.

Application of AO devices in the FSL may allow obtaining optical combs with central frequencies in the range from UV to medium IR. Due to the AO interaction peculiarities AO OFCs may be generated effectively in the UV and visible ranges and this may be treated as one of the most important features of AO combs. By installing two AO frequency shifters (AOFS) in series, shifting the optical signal frequency in opposite directions, one may obtain combs with extremely tight spacing between spectral components\textsuperscript{19}.

In this paper we continue the examination of the OFC generation in FSL scheme based on collinear geometry of AO diffraction\textsuperscript{21-23}. The collinear AO cell in this system may function both as modulator and frequency shifter\textsuperscript{24-26}. This gives the possibility to realize several regimes of OFC generation in FSL scheme. The AO cell operation mode is controlled by the rotation of the pair of polarizers between which the AO cell is mounted. The polarization planes mutual reorientation switches the OFC generation mode and allows changing OFC parameters. Here we examine the dependences of OFC characteristics on the driving RF power and frequency.

2. SYSTEM DESCRIPTION

2.1 Collinear AO interaction

Collinear AO cell\textsuperscript{21,22} is the key element for the proposed OFC generation schemes. This geometry of AO diffraction takes place when wave vectors of incident and diffracted light as well as the wave vector of ultrasound wave are collinear. The collinear AO cells are usually fabricated on the base of calcium molybdate or lithiu niobate crystals. Tellurium dioxide crystal is not applied for this purpose due to the absence of AO effect in the XY plane. In the conventional applications collinear AO cells are displaced between two polarizers. The input polarizer is used to set the polarization of incident light along one of the crystal optical eigenmodes. The output polarizer is applied to separate the diffracted light from the zero diffraction order as they propagate along the same direction but with orthogonal polarizations. The important advantage of collinear AO diffraction is that in eliminates the problem of diffracted optical beam angular dispersion.

The AO phase matching condition that sets the relation between acoustic wave frequency $f_a$ and optical radiation wavelength $\lambda$ for collinear AO diffraction is the following:

$$f_a = \frac{V}{\lambda} |n_o - n_e|$$

where $V$ is the acoustic wave velocity and crystal refractive indices for ordinary and extraordinary waves are marked as $n_o$ and $n_e$ correspondingly. Thus varying the RF frequency $f_a$ one is able to tune the central transmission optical wavelength of the AO cell. We propose to use AO cell fabricated from lithium niobate. In this case the acoustic wave will propagate along Y crystallographic axis. For optical wavelength 1.55$\mu$m the LiNbO$_3$ characteristics are the following: $n_o=2.211$ and $n_e=2.138$. Ultrasound velocity is 3940 m/s. The AO phase matching frequency turns out to be 185.96 MHz. If AO cell operates as AOFS the frequency of ultrasound wave sets the optical radiation frequency shift in obtained the FSL.

It was shown previously\textsuperscript{24-26} that conventional application of collinear AO cell is only the special case. In general, when input optical radiation has arbitrary linear polarization at angle $\alpha$ with respect to Z axis the light radiation at the AO cell output will consist of four components polarized along X and Z axis of the crystal: $E^x_0$, $E^z_0$, $E^x_1$ and $E^z_1$. The superscript here indicates the direction along which the component is polarized and the subscript – the AO diffraction order. We should note here that $-1^{st}$ and $+1^{st}$ AO diffraction orders are Doppler shifted but in the opposite directions. The magnitude of this shift corresponds to the frequency of ultrasound wave aroused in the AO cell.

Passing through the polarizer the field components acquire the same polarization and interfere. The resulting intensity after the polarizer may be written as:

$$I_g = \left| \left( E^x_0 + E^x_1 \right) \cos \beta + \left( E^z_0 + E^z_1 \right) \sin \beta \right|^2 = I_0 + I_1 \cos (\Omega t + \Phi + \phi) + I_2 \cos (2\Omega t + \phi + 2\Phi)$$

where $\beta$ defines the output polarizer polarization plane with respect to Z axis, $\Omega=2\pi f_a$, $\phi$ is the additional phase shift appearing at collinear AO interaction and $\Phi$ is the ultrasonic phase. So the output light intensity consists of three
components: constant component $I_0$, that is used in conventional collinear AO filter applications, it obtains maximal magnitude when $\alpha=0^\circ$ or $90^\circ$ and $\beta=\alpha+90^\circ$; component that obtains amplitude modulation with ultrasound frequency $I_1$; and component with amplitude modulation at double ultrasound frequency $I_2$. $I_0$ component reaches maximal magnitude when $\alpha=0^\circ$ or $90^\circ$ and $\beta=\alpha+45^\circ$, $I_2$ is maximal when $\alpha=\beta=45^\circ$. Components $I_0$ and $I_1$ may be used to obtain single side band (SSB) modulation as they are Doppler shifted in comparison with incident light. $I_2$ component may be used for amplitude modulation.

### 2.2 FSL schemes

It was shown in our previous papers\textsuperscript{23,27} that two completely different AO OFCs generation schemes are possible when applying collinear AO diffraction. Both of them are based on the Doppler shift that appears in the AO interaction process. These schemes are shown in Fig.1. The first scheme is the conventional FSL scheme with optical loop, collinear AO cell used as the AOFS and external RF generator feeding the AO cell transducer. The optical radiation from the feedback is coupled with seed laser radiation with optical coupler the optical radiation is directed to the optical spectrum analyzing system also with optical coupler.

![Figure 1. Proposed AO OFC generation schemes. The part of the scheme that is inside the brown dashed line corresponds to the optoelectronic feedback.](image.png)

The optical loop in both cases contains the half wave plate (HWP) used for optical polarization rotation, as the diffracted light has the polarization orthogonal to the incident one. It also contains optical amplifier and optical phase shifter that are used for the compensation of optical radiation phase shifts that appear in the AO diffraction process and light propagation through the optical path.

In the second scheme the RF generator is excluded but the optoelectronic feedback (all that is inside the brown dashed line) is added. This beamsplitter should be mounted before the output polarizer\textsuperscript{28-31}. One of the beams from the beamsplitter is sent to the optical feedback loop (signal beam), and the second one is fed to the electrical feedback circuit. After the beamsplitter the second optical beam (feedback beam) passes through the polarizer rotated at the angle $\gamma$ relatively to the Z axis of the AO filter. The polarizer must be oriented in such a way that the light beam at its output obtains the amplitude modulation with the ultrasound frequency (maximum of $I_1$ component). Modulated optical radiation enters the photodetector with sensitivity $\rho$ that transforms it into electric signal with the frequency equal to the frequency of the light beam amplitude modulation. It is the same frequency that the ultrasound wave excited in AO cell has. The signal from the photodetector passes through the feedback circuit with gain $\kappa$. 

---

**Downloaded From:** https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie

**Terms of Use:** https://photonicsforenergy.spiedigitallibrary.org/terms-of-use
The optoelectronic feedback consists of a phase shifter and a RF amplifier to fulfill the phase and amplitude balance conditions. The output of the feedback circuit is connected to the AO cell piezoelectric transducer with efficiency ψ.

As a result, we obtain an optoelectronic system with two feedback loops: an optical one needed to increase the number of components in the spectrum of light radiation, and an optoelectronic one, required for the diffraction of these optical components in the AO cell. Since the bandwidth of the system in the generation mode tends to zero, each spectral component is diffracted with zero mismatch, independently of the others, at its own acoustic frequency.

2.3 Process of OFC generation

The process of OFCs generation in both systems is illustrated by Fig.2.

In the simple FSL scheme (Fig.2a) the appearance of the new optical radiation spectrum components is produced by multiple pass of light through the FSL. In the double feedback scheme (Fig.2b) the seed laser radiation with a wavelength λ polarized along Z axis is fed to the optical input. The feedback polarizer is oriented at an angle γ = 45° and the gain κ is higher than the excitation threshold. Thus the oscillations with f1 frequency will be aroused in the electric feedback for each spectral component. An acoustic wave with the same frequency will be excited in the AO cell.

If the light is diffracted to the -1-st order, the optical wavelength will be shifted by Δλ1 = λf1/(c+f1λ) where c is the light velocity. In the FSL, when signal beam polarizer has orientation at an angle β = 90°, the light radiation with the wavelength λ + Δλ1 will exist. Passing through the HWP light acquires the same polarization as at the input of the AO cell. At the second passage of light through the system two spectral components with wavelengths λ and λ + Δλ1 will exist at the input. The presence of two components in the optical radiation spectrum causes the emergence of two ultrasound frequencies in the feedback circuit f1,1 and f1,2 and two acoustic frequencies in the AO cell. Wherein f1,1 > f1,2 as λ < λ + Δλ1. Optical wave λ diffracts by the first of them and λ + Δλ1 - by the second. Wherein f1,1 > f1,2 as λ < λ + Δλ1. So the optical waves with the wavelengths λ + Δλ1 and λ + Δλ1 + Δλ2 appear and Δλ2 > Δλ1. The generated OFC will be chirped as the spectral interval increases with the component number N linearly, the chirp obtained is small and depending on the AO crystal characteristics but it appears without external RF.

The output of the feedback circuit is connected to the AO cell piezoelectric transducer with efficiency ψ.

Figure 2. Process of OFCs generation. Conventional FSL scheme (a); Double feedback scheme (b).

In the case of SSB modulation, that takes place for I0 or I1 components application, the OFC spectral components appear due to the change of the optical radiation wavelength caused by the Doppler effect. The comb appears from successive diffraction of light with AO mismatch Rc by the same single-frequency ultrasonic wave, the diffracted beam at the n-th pass through the optical feedback loop is the incident light for the (N+1)-st pass. The spectral interval between the OFC components Δλ is determined by the RF generator frequency. In the diffraction in +1-st or -1-st diffraction order, chosen by the orientation of the input polarizer, the wavelength of the next spectral component is less or more than the previous one. The subsequent spectral components in SSB method are obtained only by diffraction of the previous ones. If the constant component is used only one optical wave exists at the AO cell output, so there is no phase shift between OFC components.

The presence of two components in the optical radiation spectrum causes the emergence of two ultrasound frequencies in the feedback circuit f1,1 and f1,2 and two acoustic frequencies in the AO cell. Wherein f1,1 > f1,2 as λ < λ + Δλ1. Optical wave λ diffracts by the first of them and λ + Δλ1 - by the second. Wherein f1,1 > f1,2 as λ < λ + Δλ1. So the optical waves with the wavelengths λ + Δλ1 and λ + Δλ1 + Δλ2 appear and Δλ2 > Δλ1. The generated OFC will be chirped as the spectral interval increases with the component number N linearly, the chirp obtained is small and depending on the AO crystal characteristics but it appears without external RF.
3. MATHEMATICAL MODEL AND RESULTS OF SIMULATIONS

3.1 Mathematical model

The mathematical model for both OFC generation schemes is explained in details in previous papers. It was shown there that for the simple FSL scheme the OFC spectrum after \( N \) passes of light through the system is described by the following equation:

\[
E_{in} = \nu E_{vecd} \sum_{n=1}^{N} \left[ \nu (1 - \chi) \sigma \right]^{n} \left( \frac{\Gamma}{2} \right)^{n} \prod_{m=1}^{n} \sin \left( \frac{\Gamma m}{2} \right)
\]

where \( \chi \) is the optical loss in the system, and \( \sigma \) is the gain of the optical amplifier, \( \nu \) is the optical coupler coupling ratio, \( \Gamma \) is the Raman-Nath parameter, proportional to the acoustic wave power. \( A_n = \sqrt{l^2 + R_n^2} \) and \( R_n = (2l\pi/V)(f - f_m) \)

where \( f_m \) is the AO phase matching frequency for \( m \)-th OFC spectral component and \( l \) is the AO interaction length.

It follows from Eq.3 that OFC contains as many spectral components as many passes through the optical feedback loop had happen and the \( m \)-th component magnitude is defined by the AO cell transmission function in \( m \)-th power.

In the case of double feedback system the OFC spectrum after \( N \) passes of light is described as:

\[
E_{in} = \nu E_{vecd} \sum_{n=1}^{N} \left[ \nu (1 - \chi) \sigma \right]^{n} \prod_{m=1}^{n} \sin \left( \frac{\Gamma m}{2} \right)
\]

where \( \Gamma_n \) is the Raman-Nath parameter for \( m \)-th OFC component calculated using the following relation:

\[
\Gamma_n = E_{vecd} \left[ \nu \epsilon (1 - \chi) \sigma \right]^{n-1} \prod_{m=2}^{n} \sin \left( \frac{\Gamma_{n-1}}{2} \right) \frac{\rho \kappa \psi \nu (1 - \epsilon)}{2} \sin \Gamma_n
\]

where \( \rho \) is the detector sensitivity, \( \kappa \) is the electric feedback gain, \( \epsilon \) is the beamsplitter with the splitting ratio and \( \psi \) is the AO cell transducer efficiency.

Thus, examining Eqs.3-5 it is possible to notice that the shape of simple FSL OFC is defined by AO cell transmission function that depends on the AO mismatch \( R \) and on the Raman-Nath parameter \( \Gamma \), proportional to the acoustic wave power. And contrary in the case of double feedback system the mismatch does not play any role as the AO phase matching condition is fulfilled for each spectral component of the OFC (as many acoustic waves are aroused in the AO cell as many spectral components OFC has). The Raman-Nath parameter influence only the electric feedback circuit gain needed to operate in the generation mode.

Thus, the examination of \( \Gamma \) influence on the OFC shape was done only for the simple FSL scheme.

3.2 Results of simulations

The simulations were carried for the following parameters of the system: \( \nu = 0.5, \chi = 0.3, \epsilon = 0.7, \psi = 0.9, \kappa = 0.35 \) and \( \rho = 0.7 \), the seed radiation wavelength was chosen to be \( \lambda = 1.55 \mu m \). The AO interaction length was chosen to be equal to 4 cm.

The results of the calculations carried out with Eq.(3) for the case when phase matching condition was fulfilled \( (R = 0) \) and Raman-Nath parameter vary are presented in Fig. 3.

The gain coefficient of the optical loop \( \sigma \) was varied in such a way as to get the widest possible comb for the given \( \Gamma \). Both the OFC spectrum and the AO filter transmission function plots are shown. From the results presented it is possible to conclude that \( \Gamma \) parameter does not influence the OFC envelope but it affects its spectral width and number of spectral components \( N \). With \( \Gamma \) increasing \( N \) decreases. Raman-Nath parameter influence also the AO cell transmission function as the diffracted light intensity is proportional to \( \sin \Gamma \), thus maximal AO diffraction efficiency is observed when \( \Gamma = \pi \). The spacing between OFC components is constant for all cases and for the chosen system parameters equals to \( f_{c} = 185.96 MHZ \).
Thus tuning $\Gamma$ one is able to control the number of OFC spectral lines.

Figure 3. Simulated OFC spectra and collinear AO cell transmission functions obtained for $I_0$ component and varying Raman-Nath parameter $\Gamma$. Optical gain $\sigma$ correspond to widest possible comb.

Another, simpler, way to control the number of OFC lines $N$ is to tune parameter $\Gamma$ with fixed optical gain $\sigma$. In this case optical gain is chosen to be equal to the value that is used when $\Gamma=\pi$ ($\sigma=2.98$).

Figure 4. The dependencies of number of OFC components for optimal (solid line) and fixed optical gain (dash line) and optimal gain (dotted line) values on Raman-Nath parameter.
The dependences that summarize the results of OFC simulations for varying $\Gamma$, $R=0$ and varying (Fig.3) of fixed optical gain are shown in Fig.4.

The dependence of $N$ on Raman-Nath parameter for fixed $\sigma=2.98$ is shown by dashed line. This dependence illustrates the AO diffraction efficiency influence on the OFC. As diffracted light intensity is proportional to $\sin^2 \Gamma$ the light losses in the system depend on $\Gamma$ and will be lowest near $\Gamma=\pi$. Thus OFC will contain maximal number of spectral components (290) when $\Gamma=\pi$ and $N$ reduces both for lower and higher $\Gamma$ magnitudes.

The dependence of $N$ on Raman-Nath parameter for varying $\sigma$ values is shown by solid curve. This shape of the curve in this case differs completely from that for constant $\sigma$. The amount of OFC spectral lines decreases with increasing acoustic power from 300 to 150. The dotted line shows the optimal optical gain dependence needed to obtain $N$ values shown by solid line.

The number of spectral lines depends on the AO cell spectral selectivity, thus reducing AO interaction length $l$ we may increase $N$ amount proportionally.

Another method to increase the number of OFC spectral components is to introduce the AO mismatch $R$. It appears when $f_g \neq f_c$. If $R \neq 0$ optical comb spectrum contains a local minimum and an additional maximum that does not correspond to the phase matching frequency. The minimum depth increases with mismatch The total spectral width of the comb increases with $R$ growth but simultaneously we have to increase the optical gain.

Our simulations for $\Gamma=\pi$ have shown that if $R = -2$ ($f_g = 185.9265$ MHz) the OFC contains 450 components and occupy 0.67 nm spectral band, the spacing between components equals to the frequency $f_g$. The optical comb shape simulation carried out for the mismatch $R = -3.79$ ($f_g = 185.8985$ MHz) is presented in Fig. 5. The total spectral width of the comb increases up to 0.93 nm and the number of spectral components is about 620. For comparison, if $f_g = f_c$ and $\Gamma=\pi$ the OFC spectral band is only 0.45 nm. Thus, the mismatch between the seed wavelength and the RF signal can be used to increase the optical comb width and the observed OFC broadening may be as high as two times.

Further transformations of the OFC shape with the mismatch increase occur as follows. The position of the maximum in the comb spectrum shifts to the right, the intensity of the components in the minimum decreases, number of components to the right of the minimum remains approximately the same.

The narrow spectral width of the optical combs in all cases is explained by high spectral selectivity of the AO cell. It is possible to increase the bandwidth reducing AO interaction length. For example, if we use the AO cell with $l = 0.5$ cm instead of 4 cm, the OFC spectral width will increase approximately by factor of 8.
The important point is that tuning the ultrasound frequency we are not only changing the width and the shape of the optical comb but also vary the interval between the spectral components of the comb. So one may tune all the OFC parameters.

4. CONCLUSIONS

Two OFC generation schemes based on collinear AO interaction are presented in this paper. The first variant is simple FSL system and the second one includes not only FSL scheme, but also the electronic feedback loop connecting optical output of the AO cell with the piezoelectric transducer of the same cell. In both systems OFC generation may be obtained by three various methods. The generation method is being chosen by the mutual orientation of the polarizers and the HWP in the optical feedback loop.

The influence of AO interaction parameters on the generated characteristic was examined. It is shown that the AO cell transmission function has a decisive influence on the OFC shape for in simple FSL scheme and has no influence in double feedback scheme. That is why double feedback scheme gives the possibility to generate broad OFCs.

For the simple FSL scheme the OFC simulations were fulfilled with varying Raman-Nath parameter, external generator frequency and optical feedback gain. These simulations have shown that variation of acoustic wave power aroused in the AO cell is an effective instrument to tune the number of OFC spectral components and spectral band in the case when the spectral spacing between OFC components is fixed. In the case when optical gain is fixed the widest comb is obtained when $\Gamma=\pi$ that corresponds to the maximal transmission of the AO cell. If we are able to tune the optical gain the widest combs are obtained for low $\Gamma$ values. When varying $\Gamma$ the OFC envelope does not change shape.

Another variant to tune the OFC spectral band is to apply AO mismatch that appear when RF generator frequency does not match with AO phase matching frequency for the given seed laser optical wavelength. Introducing AO mismatch it is possible to obtain OFCs twice wider than without mismatch, but in this case the spectral spacing between OFC components will vary also as it is being set by RF generator frequency. The OFC envelope in this case depends on $R$ value also.

ACKNOWLEDGEMENTS

This paper was supported by grant of Russian Science Foundation (Project 18-72-00036).

REFERENCES


