DOI: 10.61782/fa.2023.0482

forum acusticum 2023

CONTROL OF A QUASI-COLLINEAR AOTF TRANSMISSION RESPONSE BY RF SIGNAL APODIZATION TECHNIQUES

Véronique Quintard [1] **André Pérennou** [*1] **Adan Omar Arellanes** [1]
[1] École Nationale d'Ingénieurs de Brest, CNRS,
UMR 6285 Lab-STICC, 29238 Brest, France

ABSTRACT[*]

The behavior of the transmission response of an Acousto-Optic Tunable Filter (AOTF) in TeO_2 is analyzed in response to an acoustic pulse signal. With a quasi-collinear structure, the interaction length between acoustic and optical waves can be adjusted by controlling the duration of the acoustic pulses. We propose to study the selectivity and the side lobe levels of the optical transmission function for an RF signal modulated with rectangular and Hamming windows. The ability to adjust the transmission function over a large optical bandwidth can have very interesting applications.

We use a model based on Fast Fourier Transform to predict the AOTF transmission function shape. We also have developed an experimental setup to measure the diffraction efficiency as a function of optical wavelengths using optical pulses. The use of acoustic pulses involves working with "long" optical pulses (a few µs) to freeze the acoustic wave in the cell during the acousto-optic interaction. We show that the apodization windows make it possible to significantly reduce the secondary lobes and to easily control the selectivity over a large optical wavelength band. Good agreements are observed between simulations and measurements.

Keywords: *acousto-optic tunable filter, quasi-collinear interaction, RF apodization, optical transmission function.*

[*]***Corresponding author***: perennou@enib.fr.

1. INTRODUCTION

The transmission function shape of an Acousto-Optic Tunable Filter (AOTF), i.e. the diffraction efficiency as a function of the optical wavelength, is fixed by the nature, geometry, and crystalline cut of the crystal used. Once the filter has been technologically manufactured, its selectivity and side lobe levels in particular are fixed. The common practice for using AOTFs is to apply a continuous sinusoidal RF signal with a specific frequency to the piezo-electric transducer of the cell. Nevertheless, it can be very interesting to think about how to reconfigure the shape of the wavelength spectrum in time through a specific electric signal. We propose to use RF pulses of different shapes and duration to adapt the performances of the filter to several scenarios.

In this paper, we focus on an optical filter with quasi-collinear interaction, i.e. the group velocities of optical and acoustic waves are collinear [1, 2]. Thanks to this type of AOTF structure, we can control the duration of the interaction between the optical and acoustic waves. This allows us to adjust the selectivity of the AOTF. In the classical continuous regime, it is well known that the selectivity varies strongly as a function of the wavelength. The use of acoustic pulses can be useful for example, to perform a wavelength analysis with the same selectivity over a large optical bandwidth. Simultaneously, the pulse shape and the acoustic power in the cell are controlled to find a satisfactory performance for the side lobes in the transmission function in order to reduce the crosstalk between different optical wavelengths. The control of the selectivity and the level of the secondary lobes can, for example, find an interest in applications where the optical band is very large such as hyperspectral imaging [3].

Spectral and temporal behavior analysis of AOTF transmission function in response to rectangular RF pulses were performed in previous works [4]. The aim of this work consists in exploring the opportunity to use any acoustic apodized pulses by controlling the RF signal. In that case, it is necessary to apply the optical signal only when the acoustic pulse is fully formed in the AOTF. This means that it is needed to work with “long” optical pulses (a few µs) to “freeze” the acoustic wave in the cell and thus benefit from a well-defined transmission function at a given time. A synchronization between optical and acoustic pulses is then necessary.

This study is carried out with infrared wavelengths, but the results can be transposed to other optical wavelengths.

The paper is organized as follows. The section 2 is dedicated to the theoretical approach for the determination of the AOTF transmission function shape. We present the influence of the duration and the shape of the RF signal on the side lobe levels and on the selectivity. In section 3 we present the setup developed in order to measure this transmission function at a specific time. In section 4, some theoretical and experimental measurements are presented and discussed.

2. THEORETICAL DIFFRACTION EFFICIENCY

When using an RF signal with any apodization windows to control the AOTF, the classical diffraction efficiency equations are no longer valid because they are based on a continuous acoustic signal in the crystal. Then, in order to predict the filter transmission response we propose the use of a Fourier model.

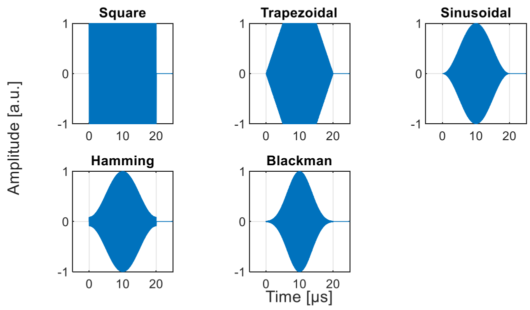
We use a diffraction efficiency simulation model based on the spectral analysis of the acoustic signal propagating in the crystal. Our approach to developing this model is based on the fact that the intensity of the diffracted beam is related to the amplitude distribution of the acoustic field in the interaction area, and therefore of the frequency distribution of the latter. The frequency distribution of the acoustic wave strongly depends on the interaction length *L*. Thus, in the model, we consider the frequency widening linked to this finite dimension *L*. The intensity of the diffracted beam for a wavelength λ is then directly linked to the power spectral density $P(f,t)$ for the frequency f of the sinusoidal RF signal. This spectral density can be expressed by the integration over the interaction time, as in Eqn. (1).

$$P(f,t) \propto \left| \int_0^{T_L} s(\tau) e^{-j2\pi f \tau} d\tau \right|^2 \quad (1)$$

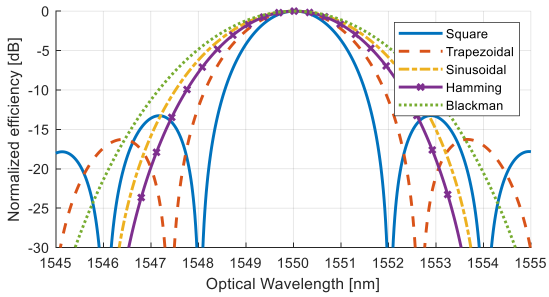
with s(t) the acoustic signal and T_L the interaction time corresponding to the interaction length divided by the acoustic velocity.

The power spectral density of the signal is calculated by FFT algorithm. A calculation is then performed to obtain the corresponding optical wavelength for each RF frequency. These calculations are based on the theoretical formula expressing the relation between the acoustic frequency and the wavelength in quasi-collinear AO interaction [2].

Fig. 1 presents the AOTF normalized transmission response for different acoustic pulse windows, like square, trapezoidal, sinusoidal, Hamming, and Blackman. The RF signal frequency was fixed to 37 MHz to obtain a central optical wavelength of the filter equal to 1550 nm. As expected, the selectivity and the side lobe level depend on the window shapes. Furthermore, by changing the duration of the interaction T_L, the selectivity can be modified.



(a)



(b)

Figure 1. (a) Different types of normalized apodization windows and (b) comparison between their normalized transmission functions obtained with the FFT algorithm. T_L=20 µs.

3. EXPERIMENTAL SETUP

Our study is based on the use of an AOTF using a quasi-collinear interaction in a TeO_2 crystal. All the measurements are performed with an optical beam incident perpendicular to the AOTF face with a diameter of 1.9 mm and an ordinary polarization. The acousto-optic cell is designed to achieve a diffraction efficiency greater than 80 % for a continuous sinusoidal RF signal, a selectivity around 1.3 nm, and a level of the secondary lobes lower than -9 dB compared to the main lobe.

We have proposed an experimental setup to measure the transmission function of the filter controlled by RF pulses (Fig. 2). We used a pulsed optical source produced by the combination of a broadband source and an optical modulator. The RF signal is generated by an Arbitrary Wave Generator (AWG). This RF signal is amplified by 42 dB and applied to the piezoelectric transducer of the cell. The electrical driver allows the management of the duration of the optical pulse via the control of the modulator as well as the synchronization of the optical and acoustic signals in the cell (delay management). The polarization of the optical beam at the input of the AOTF is controlled by a polarizer. The diffracted optical beam is collected using a focusing lens and analyzed on the Optical Spectrum Analyzer (OSA).

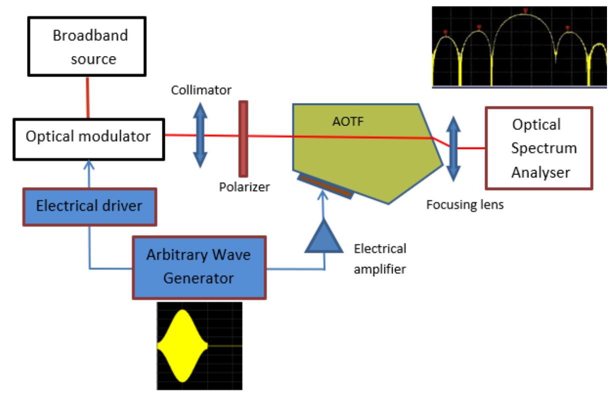


Figure 2. Experimental setup

This setup allows us to measure the relative transmission response for different RF waveforms. In the case of absolute measurements of the diffraction efficiency for a specific wavelength, we use a tunable laser source, instead of the broadband one.

For all the experiments we used optical pulses with a duration $T_{opt} = 3$ µs. It is important to verify that the sum of T_{opt} and T_L remains less than the travel time of the acoustic wave in the cell (25 µs in our case).

4. MEASUREMENTS AND SIMULATIONS

The transmission responses for square and Hamming windows are presented in Fig. 3. The RF signal frequency is fixed to obtain a central optical wavelength equal to 1550 nm. The interaction duration T_L is set at 20 µs. The mean RF power P (defined over the duration T_L) for each window is fixed in order to get 10% for the maximum diffraction efficiency at 1550 nm. This gives P = 7 mW for the square window and P = 10 mW for the Hamming window.

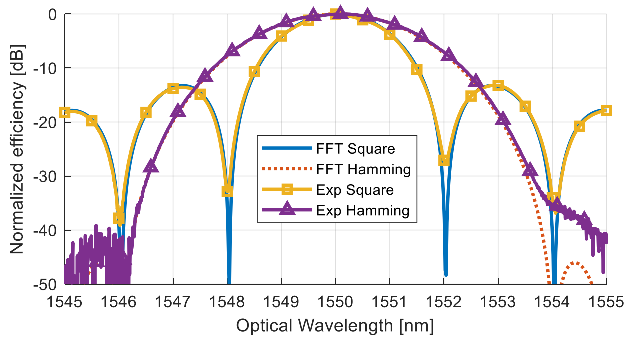


Figure 3. Normalized theoretical and measured transmission responses for square and Hamming windows. T_L=20 µs.

Fig. 3 shows also the comparison between the theoretical and experimental normalized transmission response of the AOTF for both window cases. We notice a good agreement between theoretical and measurement results with this low diffraction efficiency of 10% as we are in weak acousto-optic interaction which is the FFT domain of validity. We obtain a selectivity defined at 3 dB of about 1.75 nm for the square and 2.6 nm for the Hamming windows. Regarding the side lobe levels, we note a difference from the main lobe at 1550 nm of -13 dB for the square and less than -40 dB for the Hamming windows. As expected, the Hamming window results in almost nonexistent secondary lobes.

To get a better diffraction efficiency, we have analyzed the impact of increasing the RF power of the pulse windows on the selectivity value and the side lobe levels. We notice that the RF power has a low influence on the selectivity for rectangular [4] and Hamming windows. However, the side lobe levels are affected. For example, for the Hamming window with a maximum diffraction efficiency of 10% the side lobe level difference with the main lobe is about

-40 dB and reaches -32 dB for a maximum diffraction efficiency of 80%. For a square window and 10% maximum diffraction efficiency, this difference is about -13.3 dB and reaches -11 dB for 80%. Then, the increase of the RF power has a more important effect on side lobe levels with the Hamming windows. In order to get 80% of diffraction efficiency the RF mean power is 100 mW for square and 130 mW for Hamming. Obviously, if we reduce the pulse duration, it would be necessary to increase the RF power to keep the same diffraction efficiency.
If we want to obtain the same selectivity over a large optical bandwidth it requires adjusting the duration of the RF pulse for each central wavelength.

5. CONCLUSION

These first results show a good agreement between our FFT-based simulation model and our experimental measurements in a weak interaction regime. The model allows us to reliably predict the transmission function of the filter regardless of the characteristics of the RF signal used.
The apodization window such as the Hamming window makes it possible to significantly reduce the secondary lobes of our filter and to easily control its selectivity over the whole optical wavelength band. Of course, the minimum selectivity is given by the maximum interaction length specific to the acousto-optic crystal. The proposed method does not allow to go below this minimum value. However, the use of the Hamming window requires more mean RF power to achieve the same efficiency as the rectangular window.
The perspectives of this work consist in taking advantage of AWGs by experimentally investigating new forms of apodization of RF signals. This may lead us to see the benefit of applying multiple RF signals simultaneously to improve selectivity and reduce side lobes. It may also allow us to optimize other parameters such as the flatness or slopes of the transmission function.

6. ACKNOWLEDGMENTS

This work is financially supported by the Brittany region, the Departmental Council of Finistère, and Brest Métropole Océane, France.

7. REFERENCES

[1] I. C. Chang, “Collinear beam acousto-optic tunable filters”, Electronics Letters, 28 (13), p. 1255-1256 (1992). http://doi.org/10.1049/el:19920793

[2] V. Voloshinov, A. Tchernyatin, E. Blomme, O. Leroy, “A dozen of Bragg effects in tellurium dioxide single crystal” SPIE Vol.3581 pp141-152, Gdansk Poland, may 1998.

[3] X. Zhang and al. " High-resolution hyperspectral microscopic imaging with single acousto-optic tunable filter based on double filtering" *IEEE Access* 8 (2019): 11570-11576.

[4] A. O. Arellanes, V. Quintard, A. Perennou, “Spectral and Temporal Behavior of a Quasi-Collinear-AOTF in Response to Acoustic Pulses: Simulations and Experiments”, Appl. Opt. 61 (5), (2022). https://doi.org/10.1364/AO.449028.