Energy efficiency of lighting systems based on acousto-optic filtration

A S Beliaeva and G E Romanova
ITMO University, 49, Kronverksky pr., St. Petersburg, 197101 Russia

E-mail: belyaevalina@inbox.ru, romanova_g_e@mail.ru

Abstract. Designing systems with an acousto-optical filter requires considering its small numerical aperture and crystal size. These features lead to the low efficiency of using the luminous flux, which may be crucial in practical applications of such systems for spectral analysis. The article discusses ways to increase the energy efficiency in different types lighting systems based on acousto-optic filtration.

1. Introduction
Acousto-optic filtration allows precise spectral tuning with a possibility to change the number of selected spectral lines, their width and position. However, due to the small crystal size and limited numerical aperture, only a small part of the light flux directed by the optical system into the filter is effectively diffracted in the acousto-optical tunable filter (AOTF). The utilization rate of the luminous flux also depends on the energy corresponding to the width of the selected spectral line; the narrower the spectral line, the less energy is in the working spectral range. Additional energy losses result from absorption in the material, polarizers, and residual reflection. AOTF is the most often used in a scheme with additional polarizers, which are necessary to distinguish the working diffraction order.

Therefore, developing a source of this type it is important to analyze all the methods to increase the luminous flux's utilization. To provide this, it is necessary to consider the optimal choice of a light source, the choice of the basic optical scheme and the design of the most effective coupling optical system. It is also worth to consider another one way which is using specific crystal shapes. The latter way allows to increase efficiency due to the use of both s and p components.

2. Source
The choice of a light source should be based on the analysis of the following main characteristics:

- **Spectral distribution** determines the possible working range (we should also consider that the operating spectral range of AOTF is from 450-850 nm).
- In the system, the minimum possible beam divergence depends on the **source dimensions**.
- **Light distribution curve** determines the amount of energy directed to AOTF.
- **The luminous flux** determines the possible attainable output flux.

In accordance with the Lagrange-Helmholtz invariant, the efficiency of the system increases with the decrease of source dimensions [1]. Thus, the emitter's size should be no more than 0.2 mm (close to a point source) and with a viewing angle of 120 degrees to allow the system being developed to ideally match with AOTF. Besides, it is desirable to have the spectral radiation flux density uniformly distributed over the entire working range of AOTF [2].
Based on the set of parameters (size of the emitting surface of the source, maximum luminous flux, spectral range) we have selected two types of LEDs: XD-16 LED and XQ-E High-Intensity series due to their high luminous flux and small size. They provide the maximum luminous flux of 334 and 726 lm, respectively, from the area $1.6 \times 1.6 \text{ mm}^2$. The beam divergence is 120° and 135° for XD-16 and XQ-E, respectively [3, 4].

The chosen light sources' parameters were used at the stage of theoretical calculations of the system efficiency and in the simulation of the system in the Zemax Optic Studio [5]. The optical system's main evaluated characteristics were the concentration of the luminous flux on the area of $11 \times 11 \text{ mm}^2$ inside the angle of 5 degrees. These characteristics correspond to the angular aperture and the size of the paratellurite crystal [6, 7].

3. Optical system design

In addition to selecting the source, the choice of the principal system influences the efficiency. There exist two main variants of the beam path in systems with AOTF: confocal (figure 1(a)) and parallel (figure 1(b)).

![Figure 1](image1.png)

**Figure 1.** Principal optical schemes with AOTF: a – confocal beam path, b – parallel beam path.

The confocal scheme is the most frequently used in imaging systems. In this scheme, the intermediate image is formed inside AOTF. Therefore, the cell adds minimum aberrations [8, 9]. The diaphragm placed near the source is used to reduce the divergence of the beam. On the other hand, this leads to a significant decrease in the amount of light flux entering AOTF.

In the second variant of the scheme parallel beams of rays are incident on the cell. In such a scheme AOTF has larger aberration [8]. However, in the case of lighting systems this fact may not be crucial since the image is not formed. It is possible to collect the beam within a larger aperture and direct it at the required angle to AOTF using lenses with total internal reflection (TIR) or short-focus lenses located close to the LED (figure 2).

![Figure 2](image2.png)

**Figure 2.** Possible system with a parallel beam path: a – TIR lens, b – lens system.

In this case, both schemes cannot be assembled from off-the-shelf components. The advantages of TIR lens include the fact that this system consists of a single element, which is made of plastic and can be realized through 3D printing. Thus, fabricating of only one element is possible. In some cases, it is possible to select analogues from those available on the market, but they tend to provide a larger divergence. Besides, since the lens is located close enough to the source, plastic can deform because of strong heating of the source.

The second design consists of two short-focus lenses with three aspherical surfaces. The first lens is located very close to the emitting surface of the diode. Obviously, a miniature lens can be installed in such a position only during fabricating LED itself or if a special equipment, like a micropositioner, is
available. Otherwise, LED may be damaged or the lens surface may be deformed. Moreover, the presence of aspherical surfaces and the small size of the lenses lead to more complex and expensive production.

Modelling has shown that the system with a parallel beam path allows collecting up to 30% of the luminous flux within the useful aperture of AOTF in both systems. However, with the obtained divergence (more than 3 degrees) the unpolarized radiation from the LED source, makes it impossible to separate the zero-order diffraction from 1 and -1 orders. Therefore, to separate at least one useful diffraction order, it is necessary to use polarizing plates. In this case, the efficiency of the system is reduced to 15%.

4. Using unpolarized radiation
In the case when it is impossible to separate the diffracted order from the undiffracted rays, polarizing filters at the input and output of AOTF are used (figure 3). Using of polarizers leads to a twofold decrease in the luminous flux due to the extraction of only one s- or p- component from unpolarized radiation. Additional energy losses are caused by re-reflections and absorption in the thickness of the material.

**Figure 3.** Using unpolarized radiation in a system with polarizing plates.

To analyze the possibility of separating the diffraction orders in a system without polarizers, it is necessary to consider the work of AOTF in more detail, taking into account the birefringence in the material. In a paratellurite crystal, radiation is divided into ordinary and extraordinary rays, going at
different angles relative to the optical axis. Further, under the action of an acoustic wave, beams corresponding to 1, 0 and -1 orders of diffraction form on the grating in the crystal. Beams in orders 1, -1 (diffracted) have s polarization and p polarization, respectively. To overlap them, a polarizing beamsplitter can be used. The undiffracted rays (0 order) overlap each other and have s and p polarizations. At small beam divergence angles, separation of 0 orders is possible due to applying an absorbing screen (figure 4). However, when the luminous flux entering the AOTF has a divergence of more than 3 degrees, the orders are superimposed, and it is impossible to separate them from each other.

One of the options for utilizing the entire luminous flux is the use of the second AOTF. Thus, it is possible to separate the radiation by a polarizing beamsplitter cube and the direction s polarizing radiation into one AOTF and p polarizing radiation into the second AOTF. To separate diffracted orders in such a system, polarizing plates are used after each AOTF (figure 5).

![Figure 5. Application of two AOTFs in a system with unpolarized radiation.](image)

The dual-channel AOTF configuration can reduce the system’s dimensions [10]. Depending on the state of polarization and the geometry of the AOTF, it is possible to choose two beam incidence angles on the cell, at which the non-critical phase-matching is satisfied, and the radiation is diffracted. Although this filter’s size and cost are less than in a system with a double filter, the disadvantages of this geometry may complicate an optical system. Moreover, the efficiency of the second channel is much less.

5. Conclusion
The paper discusses the approaches to increase the utilization of the luminous flux in the lighting system with AOTF. Effective schemes are the systems, in which the emitter has the minimum size of the luminous area and the divergence. The simulation results have shown that the most efficient system is the one with a parallel beam path. In such a scheme, it is possible to direct up to 30% of the luminous flux to AOTF. The best option for matching the system is the TIR lens. It is possible to use two AOTF or dual-channel AOTF to further increase the luminous flux due to non-polarized radiation in this configuration.

References
[1] Lazarus M J, Ellarby V and Campbell D 2002 Enhanced coupling of light emitters to plastic optical fiber with the use of bulb-lens antenna systems Microwave and Opt. Technol. Lett. 33(1) 6–9
[2] Beliaeva A S, Batshev V I and Romanova G E 2021 Design of an optical illumination system for a tunable source with acousto-optical filtering Opticheskii Zhurnal 88(2) 12–19 [In Russian]
[3] XLamp XQ-E High Intensity https://www.cree.com/led-components/products/xlamp-leds-discrete/xlamp-xq-e-high-intensity

[4] XLamp XD16 https://cree-led.com/products/xlamp-leds-discrete/xlamp-xd16

[5] ZEMAX Optic Studio User Manual ZEMAX LLC p 2545

[6] Vila-Francés J et al. 2010 Improving the performance of acousto-optic tunable filters in imaging applications J. of Electronic Imaging 19(4) 043022

[7] Vila-Francés J et al. 2010 Analysis of acousto-optic tunable filter performance for imaging applications Opt. Engineering 49(11) 113203

[8] Machikhin A, Batshev V and Pozhar V 2017 Aberration analysis of AOTF-based spectral imaging systems J. Opt. Soc. Am. A 34(7) 1109–13

[9] Suhre D R, Denes L J and Gupta N 2004 Telecentric confocal optics for aberration correction of acousto-optic tunable filters Applied optics 43(6) 1255–60

[10] Machikhin A et al. 2020 Single-volume dual-channel acousto-optical tunable filter Opt. Express 28(2) 1150–7