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Technical note

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Compact AOTF-based spectral imaging system for medical endoscopic analysis

Kompaktes AOTF-basiertes spektrales Bildgebungssystem für die medizinische endoskopische Analyse

Abstract: A prototype of a spectral imaging module is described which can be attached to conventional rigid and flexible medical endoscopes. It is based on acousto-optic tunable filters (AOTF) and provides fast spectral image registration at an arbitrary series of wavelengths. The main advantage of the device is the minimization of spatial and spectral image distortion by use of a specialized double AOTF monochromator. These properties ensure immediate and reliable detection of spectral features in any image pixel. Real-time spectral analysis, in addition to spectral visualization, provides the opportunity to make medical photoluminescence diagnostics more effective.

Keywords: spectral imaging; spectroscopy; AOTF; photoluminescence diagnostics; endoscopy.

Zusammenfassung: Es wird der Prototyp eines spektralen Bildgebungsmoduls beschrieben, das an herkömmliche starre und flexible medizinische Endoskope adaptiert werden kann. Das Modul basiert auf akustooptischen Modulatoren (acousto-optic tunable filters, AOTF) und liefert schnelle Spektralbilder für beliebige Wellenlängen. Der Hauptvorteil liegt dabei in der Minimierung der räumlichen und spektralen Bildverzerrung, was durch die Verwendung eines speziellen Doppel-AOTF-Monochromators erreicht wird. Dies sorgt für die sofortige und zuverlässige Erkennung von spektralen Merkmalen in jedem Bildpunkt. Die Echtzeit-Spektralanalyse, zusätzlich zur spektralen Visualisierung, bietet damit die Möglichkeit die medizinische Photolumineszenz-Diagnostik effektiver zu gestalten.

Schlüsselwörter: spektrale Bildgebung; Spektroskopie; akustooptischer Modulator (AOTF); Photolumineszenz-Diagnostik; Endoskopie.

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1 Introduction

Photoluminescence methods are widely used in the diagnostics and therapy of tumor diseases, including cancer [1, 2]. In these applications it is especially important to analyze both the local spectral properties of the tissue and the spatial distribution of these properties. Spectral imaging systems are very informative and multifunctional instruments for real-time analysis.

Among these, systems based on acousto-optic tunable filters (AOTFs) additionally provide fast spectral access and a fairly high spectral and spatial resolution [3, 4]. Their compact design, without moving or adjustable elements, facilitates the development of portable medical spectral imaging devices. AOTF-based spectral imaging systems have been successfully demonstrated in various applications, such as for fluorescence diagnostics based on the injection of a photoluminescent substance into the organism [5], non-contact oxygen detection [6], and express-analysis of cells in blood smears [7], etc.

A further highly promising use is the application of AOTF-based spectral imagers for endoscopic spectral analysis of internal organs *in vivo*. For such purposes, AOTFs have to be coupled with medical endoscopes, both rigid and flexible [8, 9].

2 Basic problems

Almost all AOTF-based spectral imagers for photoluminescence analysis use single-cell AOTFs which results in wavelength-dependent deformations of the diffracted image [10]. No single additional spectral element is capable of correcting these distortions, and therefore images at different wavelengths differ significantly from one another spatially. This is why endoscopic imagers based on single-cell AOTFs detect spectral images lacking an exact spatial match of each other. To match them, an additional image correction procedure must be applied [11], based on a prior calibration of the imager. This makes the analysis complicated, time-consuming and less reliable.

Besides, AOTF-based endoscopic systems encounter another problem. The field of view (FOV) and the pupil of AOTFs and endoscopes differ significantly, and direct attachment of an AOTF to the endoscope output lenses causes a loss of light power and a decrease in the diffracted image quality.

An AOTF-based endoscopic imaging spectrometer is described below which minimizes energy loss and compensates for spectral and spatial distortions, thus providing fast and high-quality spectrum registration of each image pixel. An important additional feature is the modular design and compatibility with modern rigid and flexible medical standard endoscopes.

3 Hardware and software

The key feature of the optical system discussed in this paper is the sequential double acousto-optic (AO) filtration. The specific design of the double (tandem) AOTF monochromator provides almost complete compensation of spectral and spatial image distortions caused by Bragg diffraction in an anisotropic medium [10, 12, 13]. In this configuration the second AO cell is rotated by 180° around the optical axis of the system (Figure 1). The inspected object (3) is illuminated with wide-band visible or ultraviolet light from the source (1). Reflected and scattered light as well as re-emitted fluorescence radiation are transmitted through the endoscopic probe (4), the optical coupling system (5), and the AOTF monochromator (6) consisting of two AO cells and three polarizers. The spectrally selected light is focused by the objective lenses (7) onto the sensor (8) of the digital camera.

3.1 Optical coupling

The key factor affecting the sensitivity of the imager is the transfer coefficient of the AOTF monochromator. The diameter of the entrance pupil (D_{AO}=6–8 mm) is rather large compared to the exit pupil of standard endoscopes (D'_{oc}=1–6 mm), while the FOV ($2\omega_{AO}\approx 2°$) is much less than the FOV of standard endoscopic oculars ($2\omega'_{oc}\approx 20°–80°$). It is obvious that direct placement of the AOTF after the ocular of the endoscope would result in vignetting and significant energy loss.

The optimal coupler for endoscope image recording was developed using mathematical modeling by matching its entrance pupil to the exit pupil of the endoscope. The quality of the coupler should be rather high; the acceptable value of aberrations is close to the diffraction limit (0.1 mrad) in order to provide a maximum angle resolution of the AOTF monochromator (~600 resolved elements). The chromatic aberrations must be small enough to avoid the need to refocus the camera during spectral tuning of the AOTF.

This task could not be solved without the use of a double (tandem) AOTF monochromator [12, 13] which compensates the principle part of the aberrations. As it was calculated [13] spatial (angle) aberrations of single AOTF is dependent on the configuration of acousto-optic interaction and can reach 3–5% of the image size, while chromatic aberrations of tandem AOTF are approximately 10 times less.

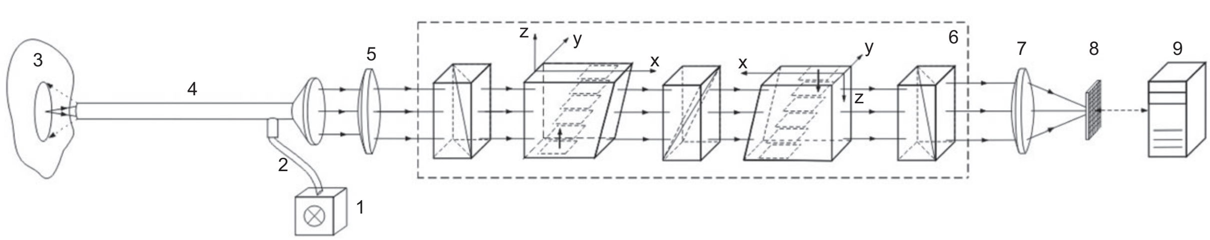

Figure 1 AOTF spectral imager for endoscopy. 1. Light source; 2. light guide; 3. inspected area of the object; 4. rigid endoscopic probe; 5. optical coupler (symbolic); 6. double (tandem) AOTF monochromator; 7. objective lenses; 8. photodetector array; 9. computer.

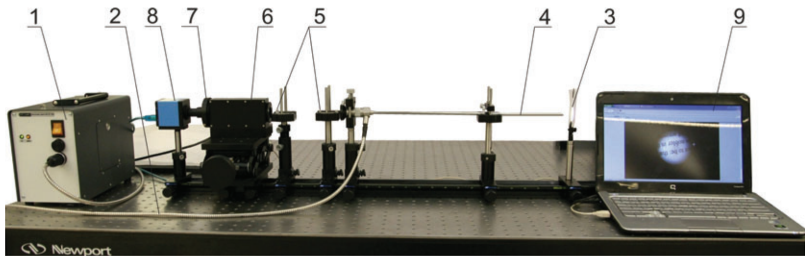

Figure 2 AOTF-based endoscopic spectral imaging system. 1. Light source; 2. light guide; 3. inspected object; 4. rigid endoscopic probe; 5. optical coupler; 6. AOTF monochromator; 7. objective lenses; 8. CCD camera; 9. computer.

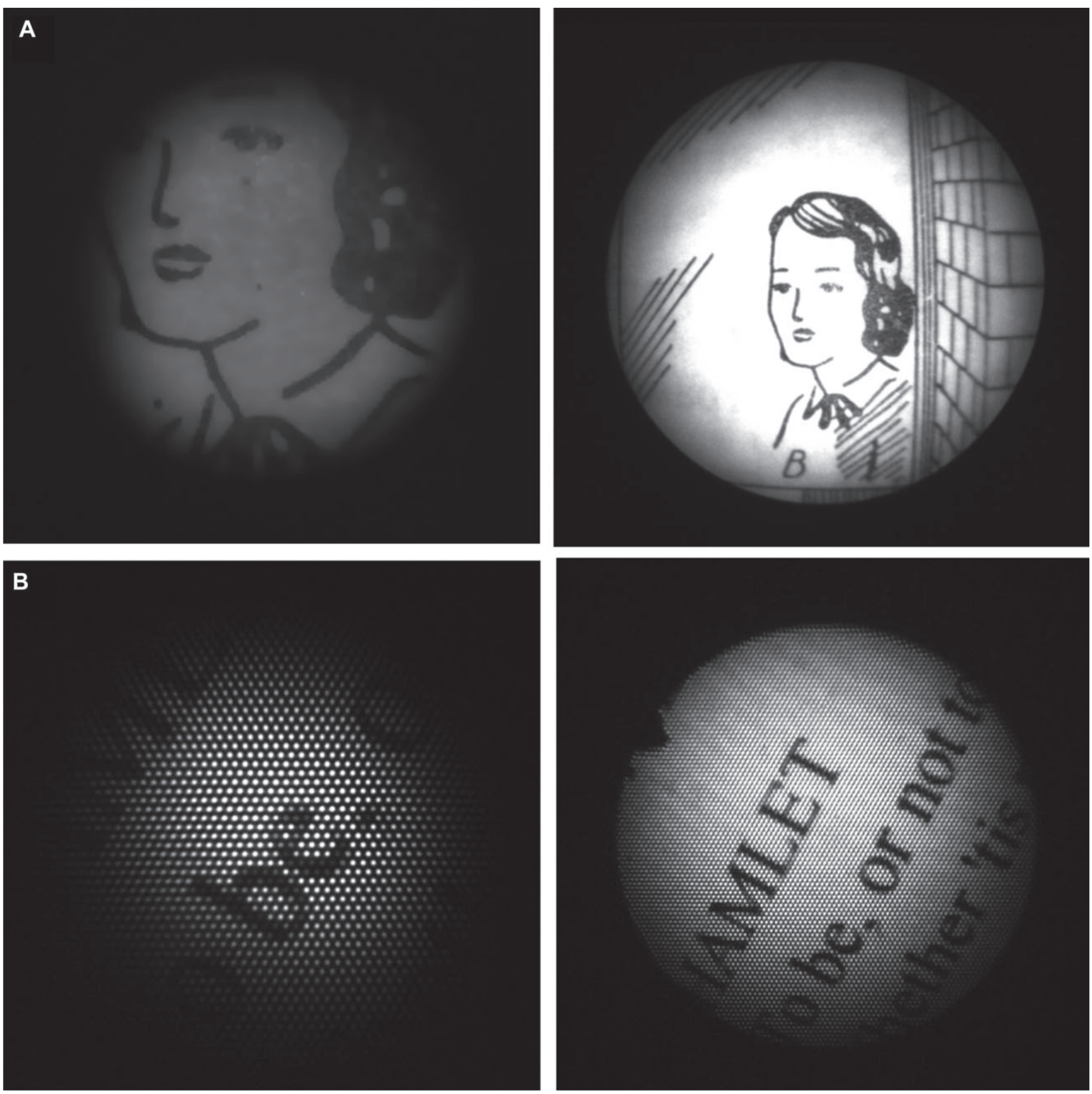

Figure 3 Spectral images (detection wavelength 650 nm) obtained under identical conditions by the AOTF-based endoscopic imager without additional optical coupling (left) and with the optimized optical coupler (right) for a rigid probe (A) and a fiber-optic bundle endoscope (B).

3.2 Prototype

The assembled prototype of the spectral imaging system (Figure 2) comprises a 100 W halogen lamp with a flexible light guide, a rigid endoscopic probe with optimized optical coupler, an imaging double-AOTF monochromator, an output objective and a monochrome CCD camera. Home-made AOTF monochromator has 8 mm entrance pupil, 2° FOV, and provides spectral resolution of 2 nm at 0.63 µm. The system is controlled by a computer in real-time mode and the spectral image of the object is displayed on the monitor.

3.3 Software

The parameters of the sensor (exposure time, gain, binning, etc.) and the wavelength of the monochromator can be tuned interactively by the user. The developed software provides both hardware control and processing of the recorded images.

There are several modes of data acquisition.

1. In hyperspectral mode, the system records images at different wavelengths in the defined spectral range. Both spectral full-images $I(\lambda_0,x,y)$ and full-spectra $I(\lambda,x_0,y_0)$ from each point of the inspected object are available for analysis.
2. In spectral imaging mode, the instrument detects images at one or several specific wavelengths $[I(\lambda_i,x,y)$, $i=0,1,2,...]$. For some applications, the bandwidth of detection can be widened by spectral scanning over a certain spectral interval $[\lambda_{min},\lambda_{max}]$, yielding an average over the corresponding interval – $\int I(\lambda,x,y)\cdot d\lambda$.
3. In chronogram mode, the device periodically collects images at a given wavelength, permitting to extract the time dependence of the luminosity for every point of the spectral image – $I(\lambda_0,x,y,t)$.

It should be noted, that the hyperspectral mode provides the total spectral-spatial information (so called hyperspectral cube), which allows results to be obtained as in mode 2 by post-processing of the recorded data.

4 Test of prototype

The developed imaging system exhibits a rather high spatial resolution: 140 elements per millimeter for central points and 75 mm^{-1} at the edge. The image quality of the system is illustrated by Figure 3, which demonstrates the basic advantages of the developed coupling system: significant expansion of the FOV and appreciable brightness increase.

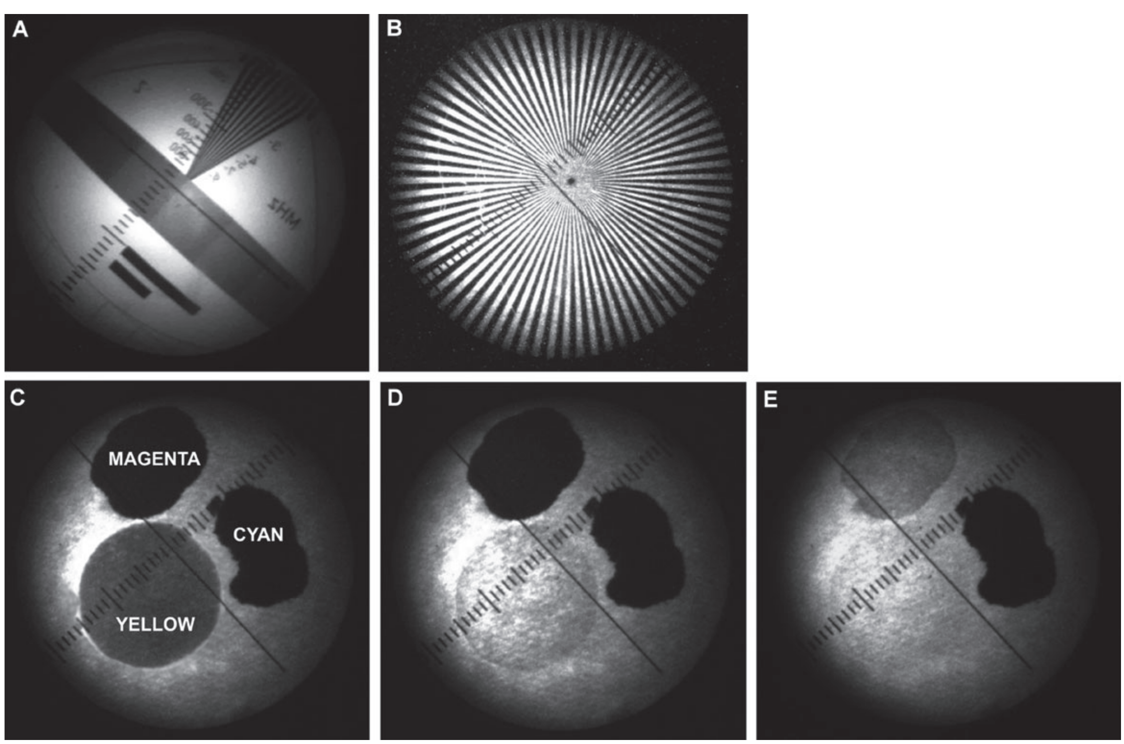

Figure 4 Spectral images of the test patterns at detection wavelength 555 nm (A, B) and of three different dye drops at different detection wavelengths: 530 nm – green (C), 590 nm – orange (D), and 670 nm – red (E).

The prototype was also tested with the use of several optical patterns (Figure 4A and B). Due to the compensated double AO filtration, chromatic aberrations in the spectral range 400–700 mm do not exceed 1% (relative spatial shift of image points between blue and red images). The spectral selectivity was tested with dye drops of cyan, yellow and magenta color (Figure 4C–E). The yellow spot stands out only at the shortest detection wavelength 530 nm which is absorbed by the yellow dye. The magenta dye absorbs wavelengths down to 600 nm, therefore the magenta spot does not provide a strong enough contrast for a detection wavelength of 670 nm in the red spectral range. The cyan dye always provides a high contrast at all detection wavelengths, which is only slightly less for detection in the green spectral range. Overall, the relative contrast in the images corresponds well to the dyes' absorption spectra [14].

5 Conclusion

The developed AOTF-based spectral imaging system has several new important features: minimum spectral and spatial image distortion, maximized optical transmission, and compatibility with standard both rigid and flexible medical endoscopes. These properties, together with programmability and compact modular design, make this instrument capable of an effective analysis and ergonomic operation in non-invasive luminescence diagnostics such as colonoscopy, bronchoscopy, gastroscopy, etc. The imager provides comprehensive spectral-spatial (hyperspectral) information and gives an opportunity for reducing the duration and the cost of endoscopic analysis.

The spectral imaging module may also be useful for technical purposes such as non-destructive testing of engines and complicated machines, pipe inspection, etc.

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