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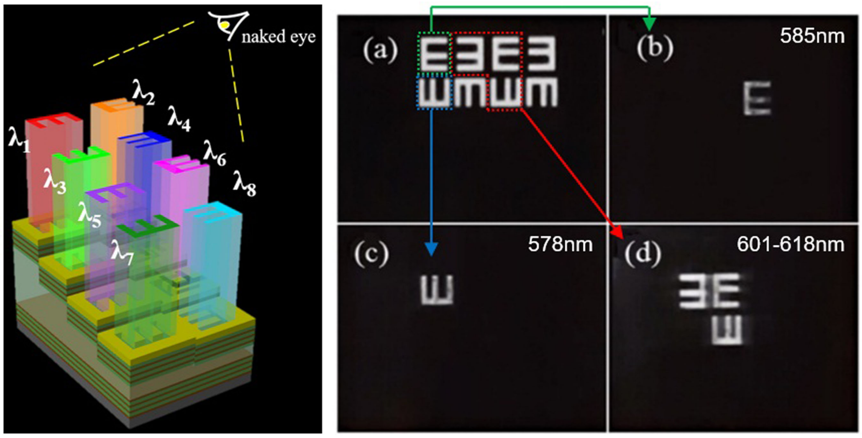

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Rapid and Precise Wavelength Determination Approach Based on Visually Patterned Integrated Narrow Bandpass Filters

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Abstract: We report a rapid and precise spectral determination approach based on visually patterned integrated narrow bandpass filters. The wavelength of light can be determined accurately even by naked eyes in the aid of the device. The experimental results show that both the light with single wavelength and a spectral range can be distinguished rapidly and precisely by naked eyes with spectral resolution higher than 7 nm, which can be even higher than 1 nm with the intended design. It is a very robust and stable way to keep the filtering wavelengths constant and remarkably improves the stability superior to conventional methods. It can be used for high-throughput identification of light source and food safety detection related applications.

Index Terms: Optical devices, Integrated optics devices, Wavelength filtering devices, microstructure fabrication.

1. Introduction

Spectroscopy is widely used in various fields of scientific research, ranging from environmental monitoring, biomedical sciences to remote sensing and space exploration [1]–[3]. It began in the 17th century after Newton demonstrated that white light could be split up into component colors and recombined to generate white light by a prism [4]. Joseph von Fraunhofer made a significant progress by replacing a prism with a diffraction grating as the source of wavelength dispersion in the early 1800s. The use of diffraction gratings improves the spectral resolution over prisms and allows for the quantification of dispersed wavelengths, which allows spectroscopy to become a more precise and quantitative scientific technique [5]. After the invention of Michelson interferometer, Fourier transform (FT) spectrometer became a very useful tool for researches, since it can simultaneously obtain high spectral resolution data over a considerably wider spectral range at a time than a dispersive spectrometer with prism or grating. Since then, spectroscopy based on prism, grating and Michelson interferometer continues to play a significant role in fields of chemistry, physics, astronomy and so on. In the past decades, some new approaches for miniature spectrometer have been developed based on various new techniques, such as acousto-optic tunable filters (AOTF) [6], integrated optical filters [7], [8], disordered photonic chip and colloidal quantum dot [9], [10].

Furthermore, wavelength determination is very important for spectroscopy to collect the right information of materials. With dispersive components such as prism and grating [11]–[13], the wavelength of light can be selected through slits by rotating the grating or prism, which is precisely controlled by the mechanical parts. Thus, the selected wavelength can be determined by the rotation angle and position of the dispersive component. However, the readout wavelength might deviate from its authentic wavelength due to the dislocation of mechanical part caused by wear, vibration and other factors, but can hardly be noticed after usage. The deviation of readout wavelength can be determined accurately only by calibration using for example, standard monochromatic light and detector with complicated and time-consuming process. For Michelson interferometer type of FT spectrometer [14], its detector monitors all wavelengths simultaneously throughout the entire measurement. An interferogram is generated by measuring of the signal at many discrete positions of the moving mirror, and then converted the measured signal into an actual spectrum by Fourier transform. The accuracy of wavelength is determined by the control precision of the moving mirror. It is problematic to determine the exact wavelength of the light, either. For other miniature spectrometers based on aforementioned new approaches, the wavelength determination is also a complicated process.

In this paper, a new method for fast and accurate determination of the light wavelength has been proposed by utilizing a patterned narrow bandpass filter. An eight-channel device has been fabricated to determine eight wavelengths of light through the patterns on each unit of device. For the new approach we proposed, one can distinguish the wavelength of light rapidly and precisely without any expensive equipment and no mechanical part. The wavelength of light can even be determined visually.

2. Design and Fabrication

The device for wavelength determination is composed of two parts: one is the integrated narrow bandpass filters for choosing the wavelengths, and the other is the particular patterns on the corresponding filter units to make them visible as shown in Fig. 1(a). For the former, different areas correspond to filters with different narrow pass bands. Each area can transmit only one specific wavelength of light. They are composed of a series of Fabry-Perot (F-P) type of filters with bottom and top mirror stacks sandwiched with a cavity layer, which can be expressed as $(LH)^m$ xL $(HL)^m$ (or $(HL)^m$ xH $(LH)^m$). L and H represent low and high refractive index materials with optical thickness of a quarter of the designed wavelength λ_0. The thicknesses of H and L are $\lambda_0/(4n_L)$ and $\lambda_0/(4n_H)$, where n_L and n_H represent the low and high refractive index of two kinds of material, respectively. The x controls the central wavelength of the passband and the number of HL stack m controls its full-width-at-half-maximum (FWHM) which corresponding to the spectral resolution. For the latter, there are different hollow patterns above each filter areas, which can intuitively correspond to the wavelengths of their pass bands. We designed different directional letter of “E” with asymmetric patterns for demonstration. Any other kinds of patterns can be designed and fabricated on the filters as long as they correspond to the size of filters.

When light illuminates on the device, each unit can allow only one specific wavelength of light to pass. As the wavelength of light is wide enough to cover all the wavelengths matching with filters, all patterns can be lighted up simultaneously as shown in Fig. 1(a). One can discriminate the

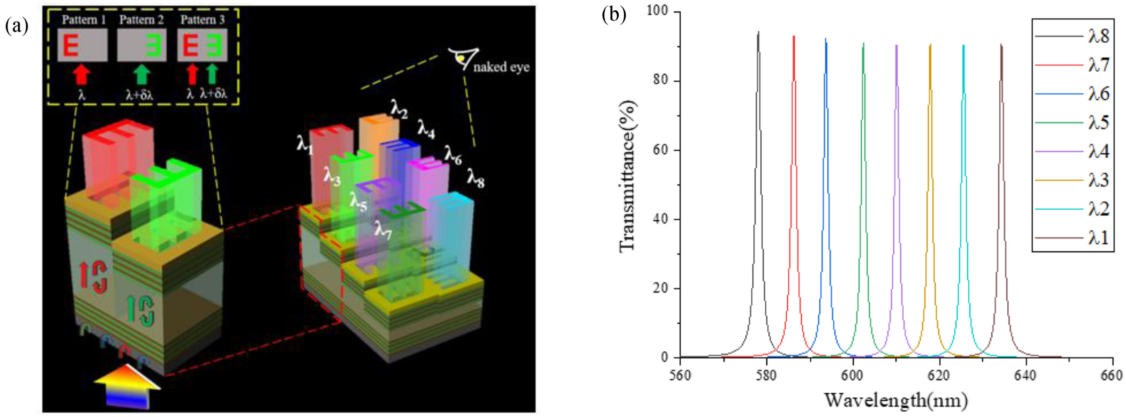

Fig. 1. (a) Illustration of the wavelength determination device when the full spectral light transmit through it, all the patterns on the device will be lighted up. The employed wavelengths of the light range from λ1 to λ8. (b) The simulated transmittance spectra of the eight filter units on the device. The central wavelengths of the eight channels are 578 nm, 586 nm, 594 nm, 602 nm, 610 nm, 618 nm, 626 nm, 634 nm, respectively, with FWHM less than 2.1 nm.

wavelength of light by checking whether the specific pattern is lighted up or not. If the size of the patterns is designed to be larger than 0.1 mm, which is the minimum discriminated limit by naked eyes, the wavelength determination can even be accomplished visually.

To demonstrate the concept of novel wavelength determination, an eight-wavelength device has been designed and fabricated as follows. The number of wavelengths can be extended to more than a hundred with special requirement by such a method [15]. The device is based on Fabry-Perot type of filter structure, which is composed of a cavity layer sandwiched by two distributed Bragg reflector (DBR) stacks. A typical narrow bandpass structure of $(LH)^m$ xL $(HL)^m$ is designed with λ_0 of 620 nm. TiO_2 and SiO_2 are chosen as the high and low index materials, respectively. Other optical materials can also be used as high and low index materials. The number of (HL) DBR stack m controls the FWHM and corresponding spectral resolution of the filter. The band width becomes narrower with the increase of m, while the fabrication difficulty will increase as well. The m is set as 6 to balance the spectral resolution of filters and its fabrication difficulty.

For a dielectric F-P filter, the peak wavelength of the passband (λ) will be

$$\lambda = \frac{2nd}{k + (\varphi_1 + \varphi_2)/2\pi} = \frac{2nd}{m},$$
$$m = k + (\varphi_1 + \varphi_2)/2\pi, \quad k = 0,\ 1,\ 2 \ldots.$$

This equation indicates that the passband of the filter is determined by the optical thickness (nd) of the spacer layer. A series of filters with different passbands can be obtained just by changing the thickness (d) of the spacer layer. x in the $(LH)^m$ xL $(HL)^m$ determines the optical thickness of the cavity, which is selected from 1.61 to 2.13 to assure the central wavelengths of all channels distributed from 578 nm to 634 nm with interval of 8 nm, as shown in Fig. 1(b). The designed FWHM of all wavelengths is less than 2.1 nm suitable for high spectral resolution applications. The central wavelength can be changed as what we designed, and the interval of wavelength can be tuned as well. To ensure that the experimental results agree well with the theoretical design, actual optical parameters of TiO_2 and SiO_2 thin films deposited by our system were extracted from the experimental transmission and reflection spectra of single layer TiO_2 and SiO_2, respectively. The detailed procedure to get the actual optical constants was presented in other publications through the transfer-matrix method [16], [17]. The refractive indices of TiO_2 and SiO_2 in this work are 2.14 and 1.47, respectively.

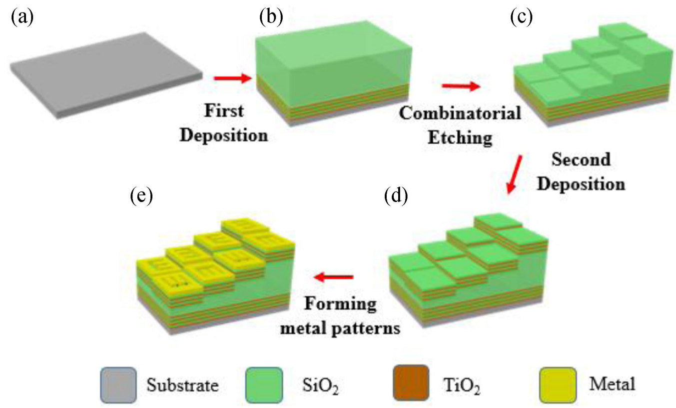

Fig. 2. (a)–(e) is the flowchart for making an eight-unit narrow bandpass filters device on a chip. (a) Substrate. (b) Bottom mirror stack with cavity layer is firstly deposited onto the substrate. (c) Eight different cavities can be obtained by combinatorial etching method. (d) Eight cavities are formed by depositing the top mirror stack. (e) Eight patterns are formed onto the eight corresponding filter units, respectively.

The fabrication process of the wavelength determination device is presented in Fig. 2. The bottom mirror stack with cavity layer and top mirror stack are deposited onto the substrate before and after the combinatorial etching steps, respectively. The bottom mirror stack and cavity layer of $(LH)^6$ 2L is firstly deposited onto the substrate of double-side polished glass (see Fig. 2(b)), where H and L represent TiO_2 and SiO_2 with physical thickness of 69.0 nm and 108.7 nm, respectively.

The deposition of the thin films was conducted by electron beam evaporation using a Leybold ARES1110 high vacuum coating system. (The vacuum pressure was about 5.0×10^{-4} mbar in the chamber, and the temperature would be increased to 200 °C and kept for one hour before deposition. The evaporation rates were 0.6 nm/s and 0.25 nm/s of SiO_2 and TiO_2, respectively. The optical thickness of the film was precisely controlled by the OMS5100 optical monitoring system.) The combinatorial etching processes were conducted on the resultant cavity layer as shown in Fig. 2(c). It took only three times of combinatorial selective etching to form eight cavities with different thicknesses, which forming 2^n thichnesses of cavities by only n times of combinatorial etching processes. The etching processes were performed by inductively coupled plasma (ICP) using Oxford PlasmaPro System 100. The two gases used for etching were argon (Ar) and trifluoromethane (CHF_3) with flow rates ratio of 1:1. The radio frequency (RF) power and ICP power were set as 100 W and 1000 W, respectively. During the combinatorial etching, the etched thicknesses of SiO_2 cavity layer were 39.2 nm, 19.6 nm and 9.8 nm, respectively. Then the top mirror stack of $(HL)^6$ was deposited onto the resultant cavities to form the eight narrow bandpass filters, as shown in Fig. 2(d). Finally, eight patterns were formed atop each filter by conducting the processes of UV photolithography, metal deposition and lift-off. Eight asymmetric letter "E"s with different orientations were used to visually distinguish the wavelengths as shown in Fig. 2(e). Other patterns can also be used as request to distinguish the wavelengths such as the numbers of their wavelengths.

3. Results and Discussion

The inset of Fig. 3 shows the size of final fabricated device with eight asymmetric "E" patterns aligned in different directions, which is less than 1 mm for each pattern. The total length of the fabricated device is less than 3 mm. Each letter "E" is atop a narrow bandpass filter and only the light with the wavelength matching the pass band can pass through it.

The transmission spectra of each narrow bandpass filters on the device have been identified by a HORIBA scientific HR800 spectrometer, as presented in Fig. 3. The central wavelengths of the eight channels are distributed between 578 nm and 634 nm with interval of about 8 nm. The

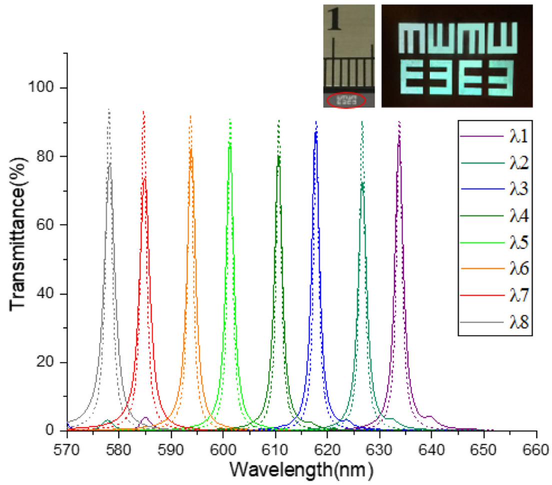

Fig. 3. The measured transmission spectra of each pattern units on the wavelength determination device, and the dash lines are the simulation results as comparison. Different colors represent different pattern units. Inset on left is the photo of fabricated eight-channel device with the full size less than 3 mm, and on right is the photo of device magnified 5 times under a microscope.

transmittance of each channel is larger than 73%, which can be further increased by adding the antireflection film to the surface of the device. The intensity of transmission spectrum is directly affected by the *k* (extinction coefficient) value of materials. The growth speed of films, vacuum and temperature, etc. in the process may increase the *k* value and absorption of the film, so that the transmittance of the actual sample is somewhat lower than the theoretical value. The FWHM of each channel is between 1.7 nm and 2.4 nm, which can be reduced by increasing the mirror stack number of *m* or the thickness of cavity layer. The FWHM is the minimum when the thickness of cavity layer is multiple of half design wavelength λ_0. It will increase when the thickness of cavity layer deviates from this condition.

To demonstrate the function of the wavelength determination of the device, a bromine tungsten lamp together with a monochromator is used as the wavelength changeable light source, to provide the light with wavelength intended. The wavelength of light is controlled and selected by the monochromator. When the device is illuminated by different wavelengths of light, the pictures are recorded by a CCD camera. We first illuminate the device directly using the bromine tungsten lamp. The eight E-letter patterns captured by the CCD are shown in Fig. 4(a). All of them are lighted up. This confirms that the introduced light covers at least the wavelengths ranging from 578 nm to 634 nm. Then the spectral resolution is adjusted to be 2 nm by changing the slit of monochromator. When the center wavelength of the monochromator is set as 585 nm, only the "E" pattern facing left (dedicated for 585 nm) is lighted up as shown in Fig. 4(b). Similar output can be observed when the selected wavelength of light changed to 578 nm, only the "E" pattern facing up (dedicated for 578 nm) is lighted up as shown in Fig. 4(c). As a result, the wavelength of light can be instantly determined visually, which can be easily examined even by naked eyes with the proposed optical filter. We can also conclude that the spectral resolution is higher than 7 nm from the results of Fig. 4(b) and (c), since the light with wavelength of 578 nm and 585 nm can be absolutely distinguished by naked eyes with the interval of 7 nm. The spectral resolution distinguished by naked eyes can be even higher than 1 nm if the FWHM and spectral intervals are designed to be smaller than 1 nm. With such a miniature optical filters, its integration with CCD sensor can generate a high-precision spectrometer that is easy for use even for a non-professional operator. Furthermore, it can also be used to identify the light source and determine its wavelength range. For example, the light with wavelength ranges from 601 nm to 618 nm can light up the three patterns corresponding to the wavelength in this region, as shown in Fig. 4(d). It can be used to rapidly and accurately check the

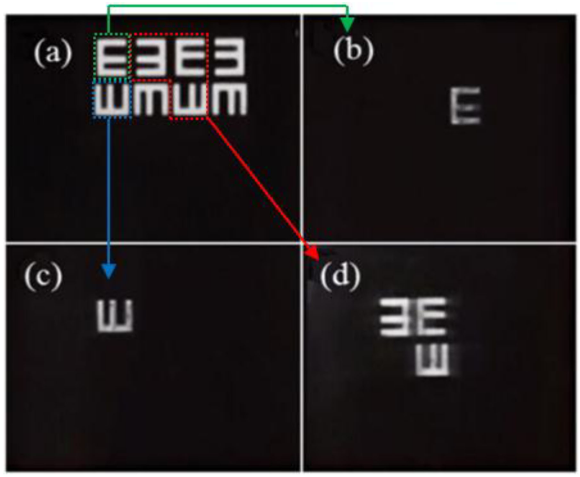

Fig. 4. Four pictures are collected by CCD when the wavelength of light source is (a) covers the range of 578 nm–635 nm. (b) is 585 nm. (c) is 578 nm. (d) covers the range of 601 nm∼618 nm.

wavelength range of LED products or other narrowband light source with small enough spectral intervals between the filters.

All the conventional spectrometers based on prism, grating or Michelson interferometer have moving part and the readout wavelength might deviate from its authentic wavelength due to the dislocation of mechanical part caused by wear, vibration or other factors, but can hardly be noticed after usage. Here, the integrated narrow bandpass filters we proposed are made of oxides and without any moving part, which are very robust and stable to keep the filtering wavelengths constant and do not need correction after usage. It remarkably improves the stability and this is another merit superior to conventional grating, prism or FTIR types. The above experimental results clearly show that the proposed method is straightforward, accurate, and more applicable than the traditional methods.

4. Conclusion and Future Work

In summary, we proposed a new mode of wavelength determination that allows direct readout of the wavelengths of light precisely by naked eyes. An eight channels device covering the wavelength range between 578 nm and 634 nm is fabricated and tested to verify the concept. One can distinguish the light with single wavelength, narrow or broadband wavelength ranges. The wavelength of monochromatic light can be determined rapidly and precisely even by naked eyes in the aid of the device. This simple and accurate spectral measurement method significantly simplifies the wavelength determination setup and process, reduces the dependence of spectrometers on the environment, shortens the measurement time, and improves the measurement stability.

Furthermore, such a concept can even be extended to the field of substance component high-throughput detection and identification. One can extend the working wavelengths of the device into the infrared (IR) range, where the absorption peaks of organic compounds are aggregated. The peak positions of each channel can be set according to the characteristic peak of the target material. One can intuitively judge if there is certain substance by observing the corresponding weakened or disappeared pattern, which is due to the absorption of the substance. Besides, one can also judge the concentration of the material based on the gray scale of the image collected by detector. We expect this miniature, fast and stable wavelength determination device to play an important role in spectroscopy.

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