A simple, low-cost demonstration of wavelength division multiplexing

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Optics and photonics can be used to motivate students in physics courses at the high school, college, or university level. Many fundamental ideas and concepts can be taught by exploring wavelength division multiplexing as used in optical fiber communication systems. We describe a safe, simple, low-cost experimental apparatus that can be used to demonstrate the key concepts of wavelength division multiplexing. The apparatus can form the basis of several hands-on, active-learning activities. © 2006 American Association of Physics Teachers.

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I. INTRODUCTION

Photonics is one of the exciting, emerging technologies of the 21st century and a great way to motivate students to study physics. For these reasons photonics has recently (2005) been introduced into the final year high school physics curriculum in Victoria, Australia. Several high school physics textbooks discuss photonics, but there are few practical photonics experiments and demonstrations for teachers to use in their classrooms. On a more global scale, UNESCO is developing a program of active-learning activities in introductory university physics education for developing countries. Some of these activities are based on optics and photonics. For both the high school and UNESCO programs, there is a need for practical, safe, low-cost photonics experiments that can be easily implemented in a classroom environment.

Several photonics teaching kits are available, but their cost is prohibitive. As an alternative, we have developed a number of very low cost photonics experiments. The experiment that demonstrates the concept of wavelength division multiplexing (WDM) as used in optical fiber transmission systems is described in this paper. This experiment is a novel extension of existing WDM demonstrations because it uses an inexpensive microcontroller and white-light LED instead of three separate LEDs and audio drivers, which are considerably more expensive and complex. Our experiment uses a simple plastic diffraction grating sheet as the demultiplexer.

II. THE EQUIPMENT

The experiment is designed around a simple white-light LED (WLED) that has three independently controlled p-n junctions (in one package) emitting red, green, and blue (RGB) light. Three current-limiting resistors can be used to adjust the intensity of the three emitted colors so that the mixture is perceived by the eye as approximating white light.

Rather than use three separate power supplies for the three color sources, an inexpensive microcontroller, in this case a PICAXE08M, is used to provide three independently controlled voltage levels to drive the RGB signals to the WLED, as shown in Fig. 1. Using a microcontroller has the added advantage of allowing different sequences of pulses to be programmed into the device to allow independent control of the driver circuits for each of the RGB signals. The microcontroller, WLED, and the driver circuitry can be built on an electronic prototyping board or incorporated into a compact printed circuit board. The components for the microcontroller/WLED can be purchased separately, or in printed circuit board (PCB) kit form or as a completely soldered printed circuit board (see Fig. 2) depending on the time and funding constraints of the user. Alternatively, a 555 timer and flip-flop combination can be used to generate a number of pulse sequences, but the microcontroller is a better solution because of its simplicity, low cost, and versatility.

The microcontroller/WLED circuit can be powered by any 4.5 to 5.5 V dc power supply, but because the circuit draws very little current it can also be operated either by 4 rechargeable AA batteries in series (giving a nominal 4.8 V) or from three alkaline AA batteries in series (giving a nominal 4.5 V).

The PICAXE08M used in this project was specifically designed for educational use. It requires only an inexpensive 9 pin to 3 pin serial RS232 cable. This interface cable is used to download the program that generates the various pulse sequences to drive the WLED. The cable can be purchased from the PICAXE supplier or the PICAXE/WLED kit supplier. The microcontroller is programmed in a version of BASIC for which a development environment, compiler, and down-loader software are freely available from the microcontroller supplier. A short program that provides pulse sequences for the WLED is available. Once the program is downloaded, the microcontroller becomes a stand-alone unit and various pulse (or dc) sequences can be selected via a simple push-button switch.

A labeled schematic diagram of the apparatus used for the WDM demonstration is shown in Fig. 3. In our case the microcontroller (A) and WLED (B) are mounted together on a printed circuit board. The three RGB light signals from the WLED are efficiently coupled via a plastic connecting tube [(I) in Fig. 3] into a 1 m length of inexpensive, high numerical aperture, plastic optical fiber [(C) in Fig. 3], which has a core diameter of approximately 2 mm. The optical fiber is very easy to work with and high quality flat end-faces can be achieved by scoring the surface of the outer layer of the fiber with a razor blade, then bending the fiber at the score mark until a crack cleaves through the cross section of the fiber. The flat end-face produced in this manner is usually sufficient for this experiment, although the end-face quality can be further improved by polishing (in a figure eight pattern) for a few minutes using a fine grade wet sanding paper. The large (2 mm) core diameter of the plastic fiber ensures efficient light coupling between the WLED and the fiber. Reasonable results can also be obtained with a smaller (1 mm) diameter core fiber.
An inexpensive 25 mm diameter plastic lens [(D) in Fig. 3] with a focal length of approximately 25 mm is positioned near the distal end-face of the optical fiber. This lens collects most of the light exiting from the optical fiber and focuses it to form a spot image on a Mylar screen [(E) in Fig. 3]. A sheet of inexpensive tracing paper can be used in place of the Mylar screen. A small (25 × 25 mm) piece of red cellophane [(F) in Fig. 3], of the type used in gift wrapping, can be positioned between the lens and the Mylar screen. The cellophane transmits only the red signal from the fiber by filtering out the other color components of the light.

For many activities the small piece of red cellophane is replaced by a similar piece of inexpensive plastic diffraction grating film. The grating is an optical dispersion element that diffracts some of the light from the optical fiber into its various (first order) color components. In this way the RGB components of the light can be split into three spatially separated images on either side of the original nondiffracted (zeroth-order) image on the Mylar screen.

If different sequences of low frequency pulses are modulated onto the RGB colors transmitted down the optical fiber, each sequence can be clearly seen in its respective RGB (spatially separated) image. More sophisticated, higher frequency signal streams can be detected as separate audio tones by replacing the Mylar screen with a carefully positioned phototransistor [(G) in Fig. 3] detector circuit (Fig. 4) whose output drives an audio amplifier [(H) in Fig. 3]. An inexpensive, high gain audio amplifier, which produces a sufficiently loud signal from a small 8 Ω speaker, can be built easily around an LM386 audio amplifier IC chip, or the amplifier circuit can be purchased in kit form. Different tone sequences (which have been modulated onto each color signal) can be heard when the phototransistor is carefully moved from one colored image to the next. The detector and audio amplifier draw only small currents and can be battery powered (in our case with a small 9 V battery).

The optical and electronic components we have discussed need to be correctly aligned with respect to each other. All of the components that require alignment (WLED, optical fiber, lens, diffraction grating, red cellophane, and phototransistor) can be mounted on holders made of wood, plastic, or aluminum. In all cases the optical components are mounted at approximately the same vertical height above a horizontal and level surface such as a table top. In addition, the mount holding the lens is fitted with a push fit plastic rod so that it can be accurately moved vertically over a range of approximately 1 cm, allowing fine vertical alignment of the image onto the phototransistor or the Mylar screen. Each component mount can also be moved in the horizontal plane to fine-tune the horizontal position and the image focus on the Mylar screen or phototransistor. The tube coupling the WLED to the optical fiber was constructed from a plastic rod with a hole drilled from one end to the other. One end of the hole was enlarged to form a push fit on the WLED and the other end is a push fit over the optical fiber. The fiber end is in contact with the WLED to maximize the light coupling [(I) in Fig. 3]. All optical mounts were made from common materials using simple equipment (for example, a drill, saw,
vise, screwdriver). Table I shown the main components used in this WDM demonstration, together with the suppliers, and their contact information.

### III. THE ACTIVITIES

The activities developed for the WDM equipment described in Sec. II are based on an active learning philosophy.¹¹–¹³ The WDM active learning session is designed as a hands-on laboratory workshop for groups of 2 to 3 students in a class of approximately 20 students, although it can also be run as an interactive lecture demonstration for larger classes.

For each activity the groups first make their predictions; the class then comes to a consensus; the groups then do the experiment and make their observations; the class discusses the observations to conclude how well they agree with the predictions; and any variations between prediction and observation are then resolved. The list of activities includes the following:¹⁴

1. Investigate the light emitted by the WLED after it has been switched on (with a constant signal applied to each of the RGB inputs). This activity is designed to expose students to a type of LED that is unfamiliar to most of them. Although the light emitted from the WLED is predominantly white, at certain angles the light will have a slight red, green, or blue dominance.

2. Investigate the image of the WLED when its light is focused onto the Mylar screen using the plastic lens. In this activity students explore image formation. They are able to observe the three separate (red, green, and blue) sources inside the WLED that add to give white light.

3. Couple the light from the WLED into one end of the plastic fiber. Then, investigate the image of the other end-face of the fiber when the light that it emits is focused onto the Mylar screen using the plastic lens. Students learn that a single optical fiber can channel light from one end to the other, but the spatial image of the three sources is not transmitted. Although the light entering the fiber comes from three separate sources, the light exiting the other end is white, showing complete scrambling of the red, green, and blue signals.

4. Investigate the image of the end-face of the optical fiber on the screen when the output state of the WLED is changed every 0.5 s according to the continuously repeated sequence: blue only, red only, green only, and then all three (R+G+B) simultaneously. In this activity students explore the concept of sending different information (carried on each of the three colors) along the optical fiber both sequentially and simultaneously. The latter introduces the idea of the WDM as a way of increasing the information carrying capacity of optical fibers. The activity also demonstrates how the three primary colors add to give white light.

5. Investigate the image of the end-face of the optical fiber when a red cellophane filter is inserted between the lens and the Mylar screen. In this activity, students explore how an optical filter can be used to isolate one color component of the light. Using one filter allows students to detect the information stream carried by one color but not the information streams carried by the other colors.

6. Investigate the diffraction pattern of the light from the end-face of the optical fiber when the red cellophane filter is replaced by a diffraction grating (where the grat-

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<td>RGB WLED</td>
<td>LEDsales (Australia)</td>
<td>RGB 5 mm 4-pin LEDs</td>
<td>$1.25AUD</td>
<td><a href="http://www.ledsales.com.au/">www.ledsales.com.au/</a></td>
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<td>PICAXE08M microcontroller</td>
<td>Revolution Education Ltd (UK)</td>
<td>AXE007M</td>
<td>£1.50</td>
<td><a href="http://www.rev-ed.co.uk/picaxe/">www.rev-ed.co.uk/picaxe/</a></td>
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<td>WLED/μcontroller Kit (complete)</td>
<td>LEDsales (Australia)</td>
<td>microcontroller RGB LED</td>
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<td>Plastic optical fiber (CK-80; 0.080 in. diam)</td>
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<td>IF-C-U2000</td>
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<td>Plastic lens 35 mm diam</td>
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<td>$0.60AUD</td>
<td><a href="http://www.oatleyelectronics.com">www.oatleyelectronics.com</a></td>
</tr>
<tr>
<td>Plastic diffraction grating film 1000 lines/mm</td>
<td>Rainbow Symphony Inc. (USA)</td>
<td>01504</td>
<td>$2.50USD</td>
<td><a href="http://www.rainbowsymphony.com">www.rainbowsymphony.com</a></td>
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<td>Audio amplifier 0.5 W kit</td>
<td>Dick Smith Electronics (Australia)</td>
<td>K5604</td>
<td>$6.00AUD</td>
<td><a href="http://www.dse.com.au/">www.dse.com.au/</a></td>
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focusing, color filtering, the dispersion of light, light modu-
photonics such as the wave nature of light, color perception,
The suggested activities cover key concepts in optics and
and low-cost WDM demonstrations. The demonstrations are
IV. CONCLUSION
We have described the experimental setup for simple, safe,
small group laboratory classes and interactive lecture dem-
strations and is ideally suited for use in situations where
cost is an important consideration.
ACCEPTED
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in constructing the apparatus.

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Advanced Components, (www.senko.com); Master Photonics Kit, Cider
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8The PICAXE08M manufacturer’s specifications advise that the voltage
used to power the microcontroller should not exceed 5.5 V, because this
will permanently damage its internal programming. We have also found
that reversing the polarity of the supply voltage has a similar effect.
9See PICAXE, (www.picaxe.co.uk).
10See EPAPS Document No. E-APJPLS-74-004605 for the basic PICAXE
microcontroller program to generate the required pulse sequences for the
WDM experiment. This document can be reached via a direct link in the
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photographs of equipment layout, are available from the authors. The
laboratory session is designed for a 2.5 to 3 h period.