An image-splitting-optic for dual-wavelength imaging

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ABSTRACT

Dual-wavelength imaging is used in several scientific and practical applications. One of the most common applications is dual-wavelength thermography which has many advantages over single wavelength thermal imaging. Optical image-splitters can be used to turn any imaging equipment into a dual-wavelength imaging system. In this paper, a new design of an image-splitting optic, for use in dual-wavelength imaging, is presented. The new design evades the limitations encountered with the basic image-splitter design where images can be captured at higher resolutions and frame rates. The new design also facilitates the adjustment of the image magnification. With very minor changes in the optical components, the image-splitter can be used in different thermal imaging techniques such as Infrared (IR) imaging and Laser Induced Fluorescence (LIF) imaging or any other technique that utilizes dual-wavelength imaging. Furthermore, with some modifications in the optical path, the image splitter can be used for imaging stepped targets. Such capability is especially useful in microscopy applications where the depth of focus is very small.

Keywords: Dual-wavelength imaging, Image-splitter, Windowing, Thermal imaging, Laser induced fluorescence, Stepped targets

1. INTRODUCTION

Thermal imaging is an essential tool in surveillance and defense applications [1,2], as well as many engineering and scientific applications [3-6]. Using thermal Imaging, the two-dimensional temperature distribution on a surface (or at a section of interest through a fluid) can be determined. While in some applications qualitative images (i.e., images showing temperature gradient) are sufficient, in other types of applications quantitative images (i.e., exact temperatures) are necessary. The multi-band or dual-band thermal imaging technique (also called ratio technique) has many advantages over single-band imaging, especially when quantitative thermal images are needed [7-10].

Two of the commonly used methods for obtaining thermal images are the infrared (IR) and the Laser Induced Fluorescence (LIF). In both techniques the lens captures the light (visible or invisible) propagated from the target being imaged and projects it on the FPA of the camera. Infrared imaging is the most widely known and used technique for thermal imaging where the IR camera captures the infrared radiation propagated from the target. Some researchers have even used the visible light radiated from hot targets to estimate temperatures [11], however such measurements are feasible only for very high temperatures (above 600° C). The other method of thermal imaging being introduced here is the Laser Induced Fluorescence (LIF) technique. During the past two decades, LIF has emerged as one of the most useful non-contact thermometry techniques. It has been used for remote temperature sensing in a variety of applications ranging from fluid mechanics to solid surface temperature measurement, and temperature ranges extending from cryogenic temperatures to those approaching 2000°C [12]. In the LIF technique, the target of interest is coated with a temperature sensitive rare-earth phosphor and the phosphor coating is subjected to a fluorescence-inducing energy (usually an ultraviolet light). A regular camera can be used to capture the fluorescence propagated from the phosphor, which is usually in the visible range. The LIF technique can also be used to capture the temperature distribution at any section of interest through a fluid where the fluid flow is seeded with the phosphor powder and the fluorescence-inducing ultraviolet light is introduced as a light-sheet through the section of interest.

The dual-wavelength technique (also called ratio technique) is used with both the IR and the LIF thermal imaging where it involves measuring the radiant energy in two different wavelength ranges and inferring the temperature from the ratio of the radiances. In IR imaging, measurement of temperature using this technique utilizes the fact that, for a grey body, the ratio of spectral radiant intensity obtained in two wavelength bands is a unique function of temperature only. The basis for effectiveness of the dual-wavelength technique is that, as long as the target follows the grey body behavior, the

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emissivity value is not required. Also, as long as the two wavelength bands are relatively close to each other, the effects of reflected radiation and contribution from the surroundings/atmosphere are eliminated (since they have the same effect on the radiances measured in the two wavelength bands).

Recently, dual-emission or "two-color" laser induced fluorescence (TLIF) has been more commonly used for temperature measurement as opposed to single color LIF. In TLIF the ratio of fluorescence intensity of two emission lines, where one emission line is temperature dependent and the other is temperature independent, is used to obtain the temperature [10]. The fluorescence intensity of the two emission lines are detected simultaneously by two sensors and the ratio of the two intensities is used to infer the temperature. The advantages of TLIF over single color LIF include the immunity of the temperature measurements to differences in the coating thickness, viewing angle, laser power, etc., between the calibration experiments and the measurement experiments.

When the target for which the temperature distribution is to be determined, using the dual-wavelength technique, has a static or near static temperature distribution (such as in steady state conditions), thermal images can be captured at different wavelength bands simply by successively using different band-pass filters in front of the camera. Furthermore, this can be automated by using different filters mounted on a rotating filter wheel synchronized with the camera such that successive frames will be captured at different wavelength bands. However, when the target of interest has a dynamic temperature distribution, not to mention that the target itself can be non-stationary, then switching filters will not do. The straight forward solution in such case is to use two synchronized cameras (with a beam-splitter in-between such that both cameras will observe the target from the same angle of view) where each capture images at a different wavelength band (either inherently or using band-pass filters). While this solution seems ideal, however, when considering the expected cost of such a system it will be seen that it will be twice of that of a single camera solution, not to mention the integration cost. It should be also noted that the price tag of cameras used in such applications (high quantum efficiency cameras, intensified cameras, IR cameras, etc.) ranges from about 10,000 to more than 100,000 US dollars, which makes the two camera solution unreasonable. Recognizing this issue, researchers have altered to the use of specialized optical image-splitters for applications requiring dual-wavelength imaging [9, 10]. Figure 1 shows a schematic drawing of the optical image-splitter used by Bizzak and Chyu [9] (a similar design was used by Goss et al. [10]). The optical image-splitter is constructed from standard optical elements (prisms or mirrors, filters, beam-splitter) and it fits between the lens and the camera. It takes the rays coming from the lens and split it in two directions, filters each part, then the two identical images (but each in a different wavelength band) are projected side by side on the Focal Plane Array (FPA) of the camera. It is obvious that the use of such optical image-splitters is very convenient where it turns any camera into a dual-band camera; however the design depicted in the figure has some shortcomings that can be circumvented. In this paper a new design for the optical image-splitter is presented. The shortcomings of the current design and the improvements achieved by the new design are discussed in detail in a later section.

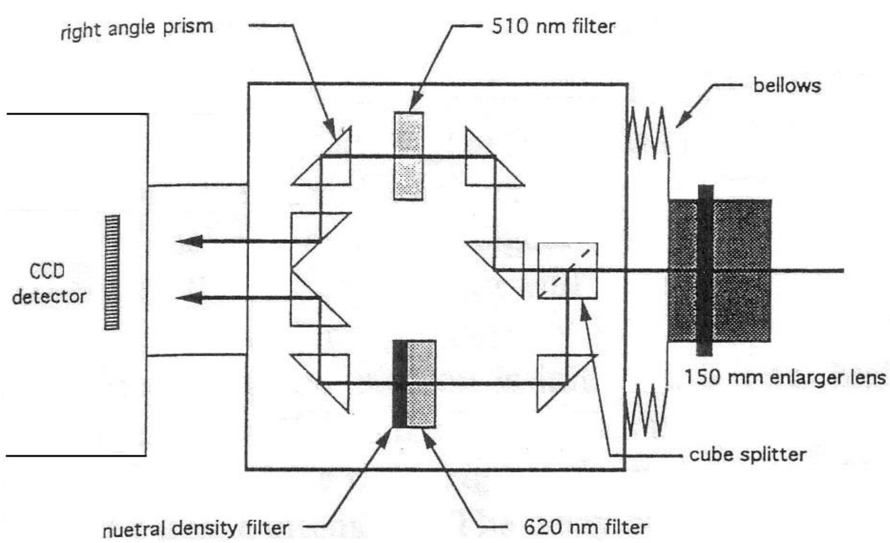

Fig. 1. Schematic of the optical image-splitter used for dual-wavelength imaging by Bizzak and Chyu [9].

2. OPTICAL IMAGE-SPLITTERS

The use of an optical image-splitter facilitates carrying out dual-wavelength thermography without the need for using two cameras. The optical image-splitter depicted in Figure 1 has two disadvantages that can be circumvented by using a more advanced optical design. These two disadvantages are; loss of image resolution and voiding the ability to perform windowing and thus increase the frame rate at which images are captured. These disadvantages can be further explained by referring to figure 2 where (a) shows an example of a target surface that is to be imaged and (b) shows the two real-images projected on the FPA (i.e., the image captured by the camera) noting that each is in a different wavelength band. As can be seen in figure 2 (b) the split-images do not occupy the entire area of the FPA which means that the images are recorded at a lesser resolution than what can be afforded by the FPA. It should be obvious that it is not possible to increase the magnification of the two images such that they will cover the FPA completely because that will cause the two images to overlap making the recorded information to be useless. Also, it is not possible to define the shape (boundary) of the images projected on the FPA (e.g., making the boundaries of the two images to be straight rather than curved such that the two images can fit side by side) since there is no intermediate real-image plane which is apparent from the absence of lenses within the image-splitter.

The read-out time for an image (i.e., the time needed to read-out the information recorded at each of the pixels comprising the image) limits the maximum frame rate that can be achieved by digital cameras [13, 14]. Windowing is a technique that can be used to reduce the time needed to read-out an image simply by reducing the size of the image (i.e., reducing the number of pixels comprising the image) and thus it increases the frame rate at which the images can be captured. This is done by defining an area of interest (AOI) on the FPA where only the information inside this area is read-out to the memory while all the photogenerated charges in the pixels outside the AOI are drained out. Referring to figure 2 (b) again, it is apparent that it is not possible to define an AOI such that it will contain the same image information in both wavelength bands. Figure 2 (c) shows how the two real-images should be projected on the FPA in order to evade the two drawbacks of the old image-splitter design (shown previously in Figure 1).

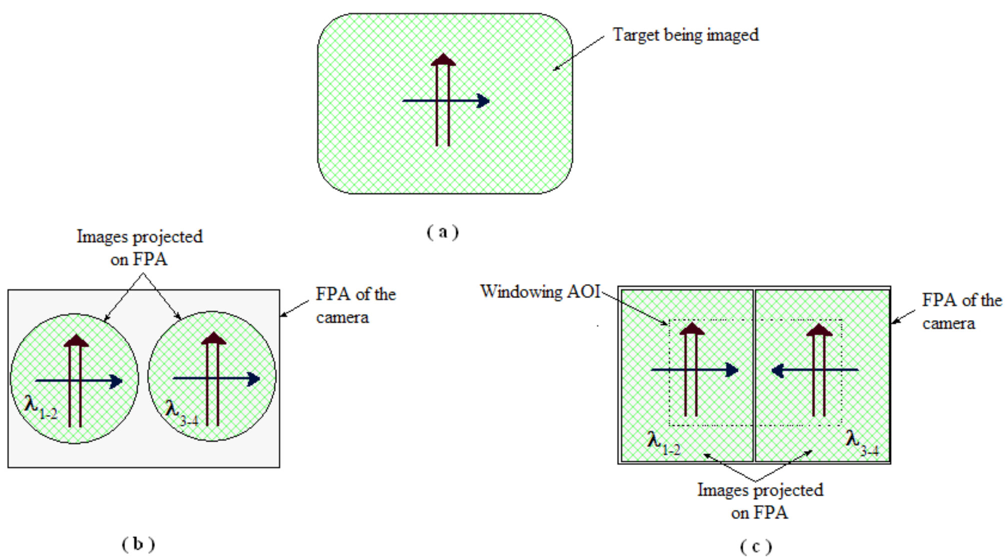

Fig. 2. Desired improvement to image-splitter; (a) The target that is being imaged, (b) The images projected on the camera FPA using the basic image splitter design, and (c) The images projected on the FPA of the camera using the new image splitter design.

As can be seen in figure 2 (c), the images should occupy the entire area of the FPA and that facilitates the use the full afforded resolution. It can be also seen that the two images projected on the FPA are mirrored (or symmetric) images (but each in a different wavelength band) such that an AOI containing the same information from the two images (as indicated in the figure) can be defined and thus windowing can be carried out to increase the frame rate. This desired improvement can be achieved by i) defining the area of the real image to have a rectangular shape such that it will occupy half of the FPA area and ii) flipping one of the two images such that two symmetric images are projected on the FPA.

3. IMAGE-SPLITTER DESIGN

A new design of an optical image-splitter for use in dual-wavelength imaging is presented in this paper. The new design evades the limitations encountered with the basic image-splitter design and images can be captured at higher resolutions and frame rates. The optical design of the new image splitter is depicted in figure 3. The new design involves standard optical components similar to those used in the old design. However, instead of projecting the real-images formed by the lens directly on the FPA, the new design utilizes a two stage image formation scheme where an intermediate real-image plane is present for each of the two optical paths and field stops are used to define the desired area of the image. The work principle of the new image splitter design can be further explained by referring to figure 3. The primary lens collects the light emanating from the target which is placed in front of the lens. A rotated view of the target is shown and it is labeled as (A). The primary lens can be any simple microscope objective lens or a more sophisticated zoom lens as long as it has sufficient back focal distance to accommodate the optical components placed in the light path (a minimum of about a 100 mm). A dichroic (i.e., wavelength selective) beam-splitter is placed immediately behind the lens such that it will split the rays coming from the lens into two different paths according to the wavelength. It should be apparent that a 50/50 beam-splitter can be used instead, however the dichroic beam-splitter is better since it will not reduce the light intensity for each of the two wavelength bands. Though a ray tracing diagram will be more illustrative, a single ray is shown only in order to simplify the figure. The ray reflected off the beam-splitter is shown in blue and it illustrates the right-hand-side (RHS) optical path while the ray passing through the beam-splitter is shown in red and it illustrates the left-hand-side (LHS) optical path. The RHS ray will be reflected off mirrors 1 through 4, respectively, while the LHS ray will be reflected off mirrors 5 through 8, respectively, before reaching the camera FPA. Mirrors 1 and 2 are arranged such that they will flip the RHS image, while no flipping will take place for the LHS image which is reflected off mirrors 5 and 6. The rays coming from the primary lens will form a real-image for each of the RHS and LHS paths, and field stops with rectangular opening are placed at the real-image planes. It should be clear that the mirrors along the two different optical paths are positioned such that the two field stops are located at exactly the same distance behind the primary lens (which is the back focal distance of the lens). The field stops are used to define the desired area of each of the two images as illustrated by the two rotated views labeled as (B) and (C) that show the intermediate real-images formed at the field stops. It can be seen that at this stage the two real-images appear to be mirrored relative to each other (in addition to being inverted by the primary lens). If desired, optional band-pass filters can be placed after the field stops in order to narrow down the two wavelength bands. Secondary lenses are used for each of the two optical paths in order to form the final real-images which are projected on the camera FPA. Mirrors 3 and 4 are positioned such that they will project the RHS image on the right half of the FPA, while mirrors 7 and 8 are positioned such that they will project the LHS image on the left half of the FPA.

As illustrated by the rotated view labeled as (D), the two images projected on the FPA will occupy the entire area of the FPA and this increases the effective resolution at which images are captured. Also, the two images projected on the FPA will be mirrored such that windowing can be used to increase the frame rate at which images are captured. Even if a simple objective lens is used as the primary lens, the new design will permit the adjustment of the image magnification by moving the objective lens relative to the beam-splitting optic (additional magnification can also be realized by the secondary lenses). With very minor changes in the optical components, the image-splitter can be used in different thermal imaging techniques such as Infrared (IR) imaging or Laser Induced Fluorescence (LIF) imaging or any other technique that utilizes dual-wavelength imaging.

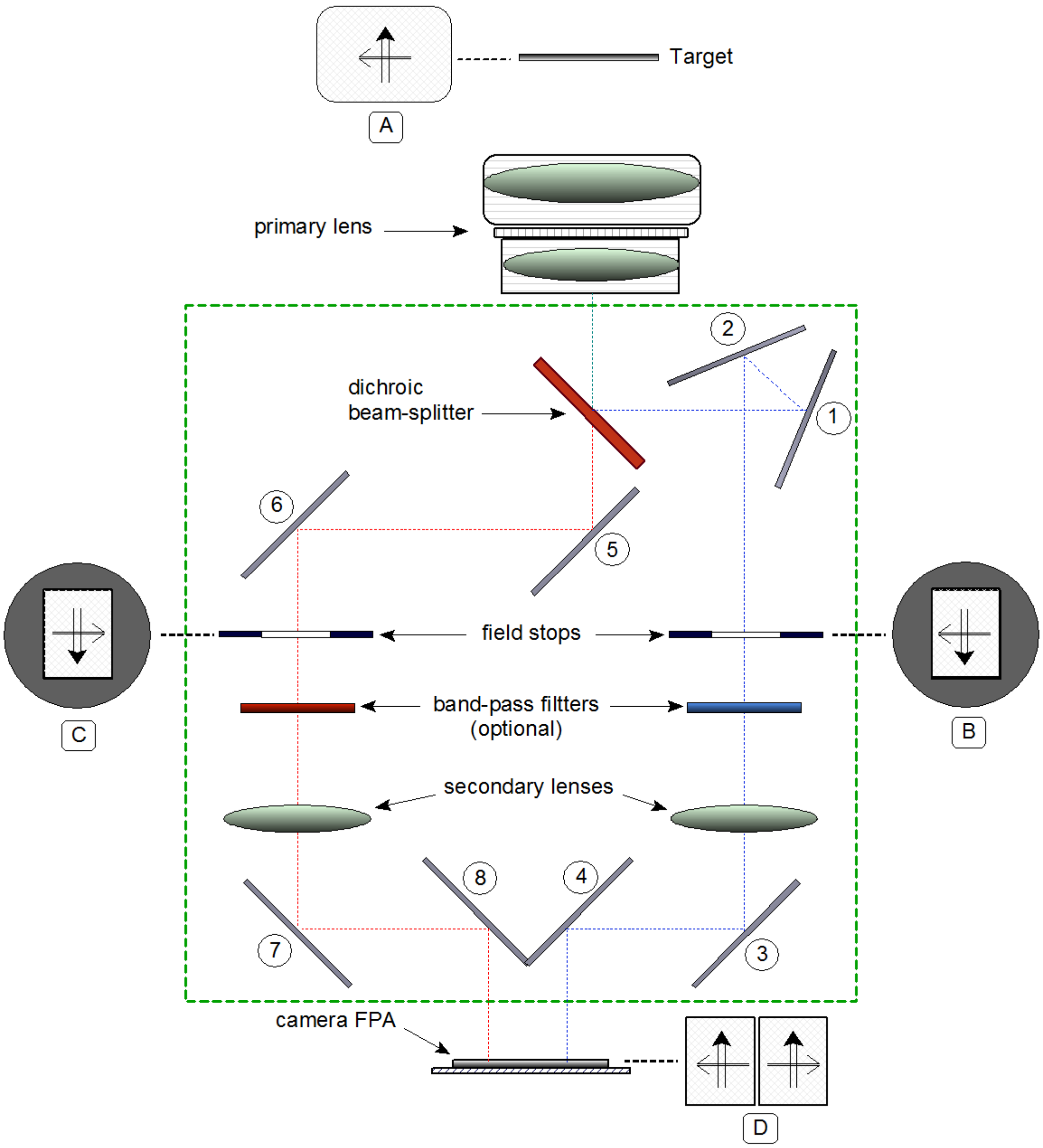

Fig. 3. The optical design of the new image splitter. (1 through 8: front surface reflection mirrors; A trough D: illustrative rotated views of the target, RHS & LHS field stops at the intermediate real-image planes, and the real images projected on the FPA, respectively)

Furthermore, with some modifications in the optical path, the image splitter can be used for imaging stepped targets (i.e., targets with two distinct portions where each is at a different height). Such capability is especially useful in microscopy applications where the depth of focus is very small. As a result of the small depth of focus, the two portions of a stepped target can not be in focus at the same time. With some modifications, the image splitter presented herein can be used for imaging stepped targets where the two portions of the target can be in focus simultaneously. The essence of the idea is to adjust the path length for one of the optical paths in order to bring a different plane in focus at the intermediate image plane. As such, it is possible to compensate for the height difference between the two portions of the stepped target. Figure 4 depicts the modified image splitter design such that it can be used for imaging stepped targets. As can be seen in the figure, only a few components of the beam splitting optic have to be replaced or just repositioned. Thus, for brevity only those changes will be discussed. A 50/50 beam-splitter is used instead of the dichroic beam-splitter since both portions of the target will be imaged in the same wavelength band. A major modification took place in the RHS optical path where three mirrors are being used rather than two. It should be noted that such configuration of the mirrors will not cause the RHS image to be flipped as previously. Mirrors 1 and 2 are placed on a translating stage (as indicated in the figure) such that the length of the RHS optical path can be adjusted. By adjusting the length of RHS path, both of the RHS and LHS intermediate images can be simultaneously in focus at the location of the field stops. It should be apparent that the LHS image needs to be focused first then the RHS image can be focused by translating mirrors 1 and 2 back or forth. As can be seen in the rotated views labeled as (B) and (C), the openings of the two field stops are located on opposite sides such that only one half of the stepped target will be in view at each of them. The secondary lenses will see the unblocked portions of the RHS and LHS intermediate real-images (where both are in focus) and will form the final real-images. The position of mirrors 5 and 9 is slightly adjusted (as compared to figure 3) where the mirrors are translated upwards (relative to the figure) in order to bring the final real-images closer to each other such that they are projected side by side on the FPA as can be seen in the rotated view labeled as (D).

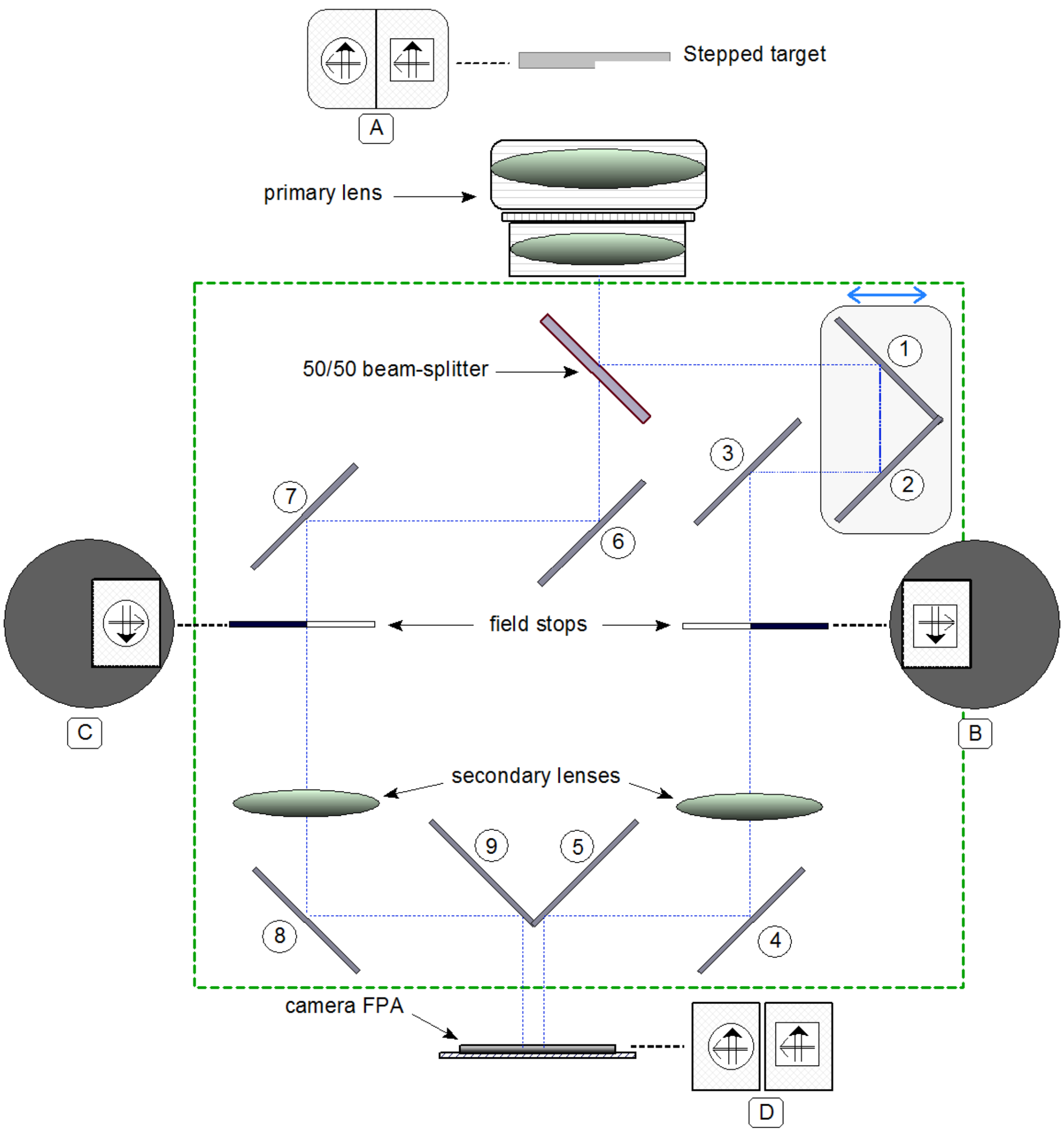

Fig. 4. The modified design for imaging stepped targets. (1 through 9: front surface reflection mirrors; A trough D: illustrative rotated views of the target, RHS & LHS field stops at the intermediate real-image planes, and the real-images projected on the FPA, respectively)

4. CONCLUDING REMARKS

The use of optical image splitters is very useful in thermal imaging where they can turn any camera into a dual-band camera. In this paper, a new design of an optical image-splitter for use in dual-wavelength imaging is presented. The new design evades the limitations encountered with the basic image-splitter design and images can be captured at higher resolutions and frame rates. The new design utilizes two stage image formation where an intermediate real image plane is present for each of the two optical paths and field stops are used for defining the desired area of the image. The two images projected on the FPA will occupy the entire area of the FPA and this increases the effective resolution at which images are captured. In addition, the two images projected on the FPA will be mirrored such that windowing can be used to increase the frame rate at which images are captured. Furthermore, with some modifications in the optical path, the image splitter can be used for imaging stepped targets. Such capability is especially useful in microscopy applications where the depth of focus is very small.

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