Multispectral Beam Splitter from Visible to MWIR

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Abstract

Electro-optical/infrared multispectral systems are being developed for a variety of defence and commercial systems applications. An ability to detect and recognize the low-contrast and distance targets in a complex environment is of great importance for many applications. The development of such systems requires special optical filters which can separate the different bands as per the requirement. We have designed and simulated these two beam splitters at 45° angle of incidence that will be applied to separate the bands from visible to MWIR. For such an optical system, the beam splitter must separate the MWIR (3600-4900nm), SWIR bands (900-1700nm) and, visible (400-700nm). In this paper, we have reported thin film coating design and simulation of these two beamsplitters. The first beam splitter is used to separate MWIR from visible and SWIR. The MWIR is in the reflection channel and the other two bands are in the transmission channel. The second beam splitter separates the remaining two bands, visible and SWIR. The visible is in the reflection channel and the SWIR is in the transmission channel.

1. Introduction

Electro-optical/infrared multispectral¹⁻² systems are being developed for a variety of defence and commercial systems applications. An ability to detect and recognize the low-contrast and distance targets in a complex environment is of great importance for many applications. The combination of the sensors in the platform improves significantly the operational use. To increase the image detection and recognition probability, most multispectral imaging systems capture images at different wavelengths and fuse the produced images using different image fusion methods. The development of such systems requires special optical filters (beamsplitters) which can separate the different bands as per the requirement.

We have designed and simulated these two beam splitters that will be applied to separate the bands from visible to MWIR. For such an optical system, the beam splitter must separate the MWIR (3600-4900nm), SWIR bands (900-1700nm) and, visible (400-700nm). Two beamsplitters are used for such a multispectral system, the first beam splitter is used to separate the MWIR in the reflection channel, visible and SWIR in the transmission channel. The second beam splitter is used to separate out remaining two visible and SWIR band. In the second beamsplitter the visible is in the reflection channel and SWIR in the transmission channel.

Beamsplitters are available in two configurations. The simpler one has the coating exposed to air, whereas in the other, the coating is immersed in a medium with an index close to that of the substrate. The latter type is frequently in cube geometry with the coating deposited on a face diagonal surface. Plate beam splitter and cube beam splitter has their own advantage. Cube beam splitter is used for optical systems where there is a requirement of minimum aberration. The cube beam splitter is rugged as the coating is not exposed to the environment. In plate beam splitter multilayer dichroic coating is deposited on one of the surfaces of a plate and the other side is coated with antireflection coating. While

in the cube beam splitter the dichroic coating is done on the hypotenuse of the prism and the prism is cemented with optical adhesive which has a similar refractive index as of a substrate.

2. Design And Simulation

Most multispectral devices adopt multi-aperture and multichannel optical systems to capture the information of the target, thus increasing the size and weight of the whole system. A common-aperture multispectral system makes the system compact. The multispectral imaging system is composed of many optical components consisting of common aperture optics, beam splitters and other optical components for different channels. The beam splitters are one of the critical components of these kinds of multispectral imaging systems. The challenge here is develop such kind of optical coatings which will filter out different wavelength at respective bands. A schematic of multispectral imaging system is shown in Fig. 1. The optical system contains a common aperture and two beam splitters: beam splitter1 (BS1) and beam splitter (BS2). The two configurations of the imaging system are shown in Fig. 1, the detailed design and simulation of these two configurations is discussed in next section.

A. Design of beamsplitter (BS1): One of the critical components of this multispectral optical system is the first beamsplitter (BS1). The output of this beamsplitter will determine the system's overall performance. The greater the transmission and reflection we can achieve, the better our overall output performance and system range. When designing a beamsplitter or filter, we must take into account the appropriate substrate, coating materials, fabrication capabilities of a coating system, and overall fabrication cost of the filter. There are two possibilities in the case of BS1. The first is to design dichroic coating such that MWIR band is in the transmission channel while reflecting the visible and SWIR in the reflection channel. The second alternative is to design the thin-film coating such that the MWIR is in the reflection channel, while the visible and SWIR are in the transmission channel.

For the development of a multispectral imaging system, the two methods presented in Fig. 1 as a viable option. In the Fig. 1a the MWIR channel is illustrated in the transmission band, whereas the visible and SWIR channels are in the reflection band. For the Fig. 1a the suitable substrate materials for BS1 includes MgF_2 , CaF_2 , ZnS , ZnSe , and sapphire.

TFCALC³ software was used to design a dichroic⁴⁻¹⁰ coating with 34 layers of coating materials such as SiO_2 , TiO_2 , ZnS , and ThF_4 on the front surface of a CaF_2 substrate. The front surface of the BS1 has a thickness of 3572nm and the rear surface has a single layer of MgF_2 with a thickness of 199nm. In the visible and SWIR channel the average transmission of 83% and 83% is achieved, while in the MWIR channel an average reflection of 89% is obtained. The performance of the BS1 mentioned in Fig. 1a is shown in the Fig. 2.

For the second configuration of an imaging system as illustrated in Fig. 1b, the suitable substrate materials for BS1 includes BK7, MgF_2 , CaF_2 , ZnS , ZnSe , sapphire etc. The dichroic coating for the front

surface of the beamsplitter (BS1) was designed using (a) all-dielectric and (b) metal-dielectric configurations.

All-dielectric

The thin-film coating for the front surface of BS1 (schematic Fig. 1b) was designed using a combination of SiO_2 , TiO_2 , ZnS , and ThF_4 . The thickness of thin film coating for the front surface is 3331nm with 36 layers of SiO_2 , TiO_2 , ZnS , and ThF_4 . The rear surface of the filter was designed using a single layer of MgF_2 . Average transmissions of 87% is obtained in the visible and SWIR wavelength regions, whereas average reflections of 72% is obtained in the MWIR wavelength region. The transmission curve for BS1 using all-dielectric materials is displayed in Fig. 3.

Metal-Dielectric

The combination of metal-dielectric¹¹⁻¹² materials with a non-quarter thickness was used for the design of this beam splitter on BK7 using TFCalc software. The coating materials used in the design includes Al_2O_3 , Ag, Si_3N_4 , and SiO_2 . The front surface of the filter has a thickness of 608nm while a single layer of MgF_2 was used to the filter's rear surface. The thickness of 199nm of MgF_2 for the rear surface of BS1 is same for all-dielectric and metal-dielectric coatings. In order to demonstrate the entire spectrum, I have deliberately taken CaF_2 as a substrate material in Fig. 4. The same spectrum of Fig. 4 is shown separately in Fig. 5 and Fig. 6. Average transmissions of 86.8% and 84.8% is realized in the visible and SWIR wavelength regions, respectively, while average reflections of 81.28% is attained in the MWIR wavelength region.

B. Design of beamsplitter (BS2): Based on the number of layers, thickness and overall performance of the BS1 we have selected the second option Fig. 1(b) for our imaging system. For BS2 as a result, the transmission channel was selected for the SWIR region and the reflection channel was chosen for the visible region. For the BS2, we have selected BK7 as the substrate material. The beamsplitter was designed for the 45° angle of incidence (AOI) thus splitting the incoming beam into two spectrum bands i.e., reflection (Visible, 400-700nm) & transmission (SWIR, 900-1700nm). The transmission and reflection curve for the BS2 is shown in Fig. 7 and Fig. 8 respectively. The average transmission in the SWIR wavelength region is 90.09%, whereas the average reflection in the visible wavelength region is 88.37%. The coating materials used for the front surface are TiO_2 and MgF_2 . The rear surface of the BS2 beamsplitter was designed with a multilayer of TiO_2 and SiO_2 .

3. Result And Discussion

The beamsplitter for the multispectral imaging system from visible to MWIR region was designed and simulated using TFCalc software. The beamsplitter BS1 is one of the important filters which basically decide the overall footprint of the imaging system. As stated in the previous section that two different possibilities for the BS1 was explored. As per Fig. 1 (a) the BS1 was designed for this configuration and

its performance is shown in Fig. 2. For the schematic shown in Fig. 1(b) the performance of the BS1 is shown in Fig. 3 and Fig. 4. Based on the results of BS1 displayed in Fig. 2, Fig. 3 and Fig. 4, the metal-dielectric layer combination shows minimum number of layer and lowest thickness. In schematic 1(a) for BS1, number of layers required was 34 with a thickness of 3572nm for the front surface. In Schematic 1(b) for BS1 (i) for all dielectric, number of layers required was 36 with a thickness of 3331nm, (ii) for metal-dielectric, number of layers required 11, with a thickness of 608nm.

A metal-dielectric-based BS1 (Fig. 1b) is made up of a 11-layer of Al_2O_3 , Ag, Si_3N_4 , and SiO_2 on a BK7 substrate, as shown in Table 1. Two metals aluminium (Al) and silver (Ag) are the suitable choice for the filter but the ratio of extinction co-efficient over refractive index of Ag has an upper edge with better rejection band. The combination of dielectric material is also important when designing filters with Ag. The Ag selection encompasses the choice for selecting Al_2O_3 and Si_3N_4 as one of the dielectric materials. The Al_2O_3 ensures the adhesion of Ag while Si_3N_4 confirms the durability of the filter.

Table 1
Metal-Dielectric based BS1(400-5000nm)

S.No	Material	Thickness (nm)
1.	Al_2O_3	82
2.	Ag	3.93
3.	Al_2O_3	41
4.	Si_3N_4	11.93
5.	SiO_2	264.27
6.	Si_3N_4	30.5
7.	Al_2O_3	25.66
8.	Ag	4.82
9.	Al_2O_3	25.66
10.	Si_3N_4	26.89
11.	SiO_2	91.56

Based on the above result the BS2 was designed with schematic shown in Fig. 1(b). The SWIR and the visible region were chosen in the transmission and reflection channel respectively. The coating design for the BS2 for the dichroic region is shown in Table2 while for the antireflection coating (ARC) for the SWIR the coating design is shown in Table3.

Table 2
BS2 (400-1700nm)Front surface
dichroic coating

S.No	Material	Thickness (nm)
1.	MgF ₂	103.58
2.	TiO ₂	45.51
3.	MgF ₂	82.70
4.	TiO ₂	39.35
5.	MgF ₂	83.29
6.	TiO ₂	53.46
7.	MgF ₂	113.65
8.	TiO ₂	58.67
9.	MgF ₂	124.04
10.	TiO ₂	68.65
11.	MgF ₂	123.6
12.	TiO ₂	63.06

Table 3
BS2 Rear surface ARC (900-1700nm)

S.No	Material	Thickness (nm)
1.	TiO ₂	30.55
2.	SiO ₂	100.28
3.	TiO ₂	157.90
4.	SiO ₂	11.07
5.	TiO ₂	109.36
6.	SiO ₂	241.62

Table 4
BS1 performance

S. No	BS1	Figure 1(a)		Figure 1(b)			
				All-dielectric		Metal-Dielectric	
		R/T	Thickness/number of layers	R/T	Thickness/number of layers	R/T	Thickness/number of layers
1.	Visible	R ~ 83%	3572nm 34 layers	T ~ 87%	3331nm 36 layers	T ~ 86.8%	608nm 11 layers
2.	SWIR	R ~ 83%		T ~ 87%		T ~ 84.8%	
3.	MWIR	T ~ 89%		R ~ 72%		R ~ 81%	
The rear surface of BS1 has same thickness for all							

4. Conclusion

TFCalc software was used to design and simulate the beamsplitter for the multispectral imaging system, which ranged from visible to MWIR. The beamsplitter BS1 is an important and critical component that determines the overall footprint of the imaging system. Figure 1 shows the schematic used to design the BS1. Table 4 summarises the transmission/reflection data. The BS1 (Fig. 1(a)), in this configuration, the MWIR band is in the transmission channel, and the overall coating thickness requirement is 3572nm with 34 layers. The BS1 (Fig. 1(b)), in this configuration, the MWIR band is in the reflection channel, and the overall thickness of the coating requirement is 3331nm with 36 layers for all-dielectric configuration, while 608nm with 11 layers for metal dielectric configuration. The metal-dielectric configuration outperformed the all-dielectric based BS1 (Fig. 1). (b). Figure 1(a) shows that the MWIR region has a better transmission of 89%, while the visible and SWIR regions have a reflection of 83% with a good output. While the metal-dielectric-based BS1 performed better in the visible and SWIR, it generated an output (R81%) in the MWIR.

With a minimum thickness requirement, the metal-dielectric filter combination is an appropriate choice. The use of silver as a metal layer in conjunction with appropriate coating materials increases the coating's durability. We chose BS1 (metal-dielectric coating) and BS2 combinations as suitable filters for our multispectral imaging system based on the coating design.

Declarations

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Declaration of interests

- The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nil

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Figures

Figure 1

Schematic of multispectral imaging system

Figure 2

Transmission curve for BS1: Visible, SWIR & MWIR wavelength region

Figure 3

Transmission curve for BS1 using all-dielectric: Visible, SWIR & MWIR wavelength region

Figure 4

Transmission curve for BS1 using metal-dielectric: Visible, SWIR & MWIR wavelength region

Figure 5

Transmission curve for BS1 using metal-dielectric: Visible & SWIR wavelength region

Figure 6

Reflection curve of BS1 using metal-dielectric: MWIR wavelength region

Figure 7

Transmission curve for BS2: SWIR wavelength region

Figure 8

Reflection curve for BS2: Visible wavelength region