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(54) **Title:** LIGHTGUIDE OPTICAL ELEMENT FOR POLARIZATION SCRAMBLING

Fig. 1 (PRIOR ART)

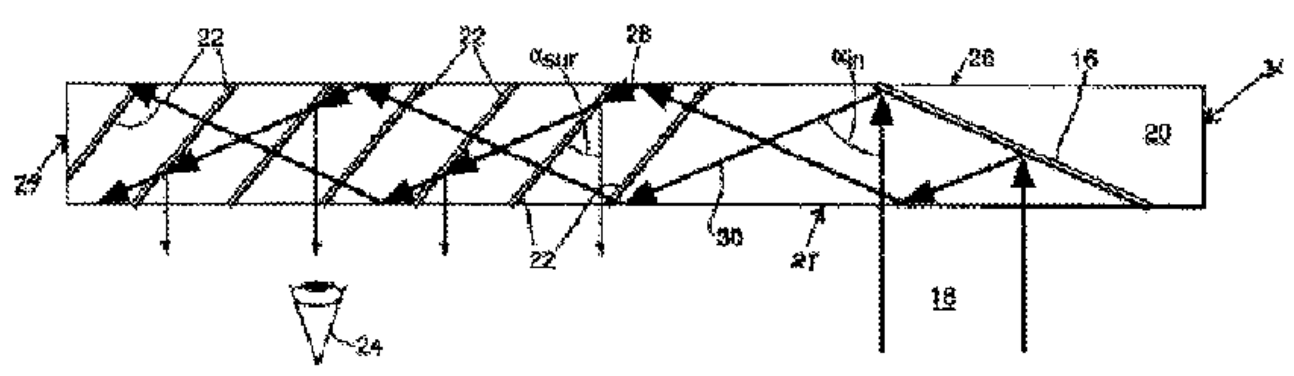
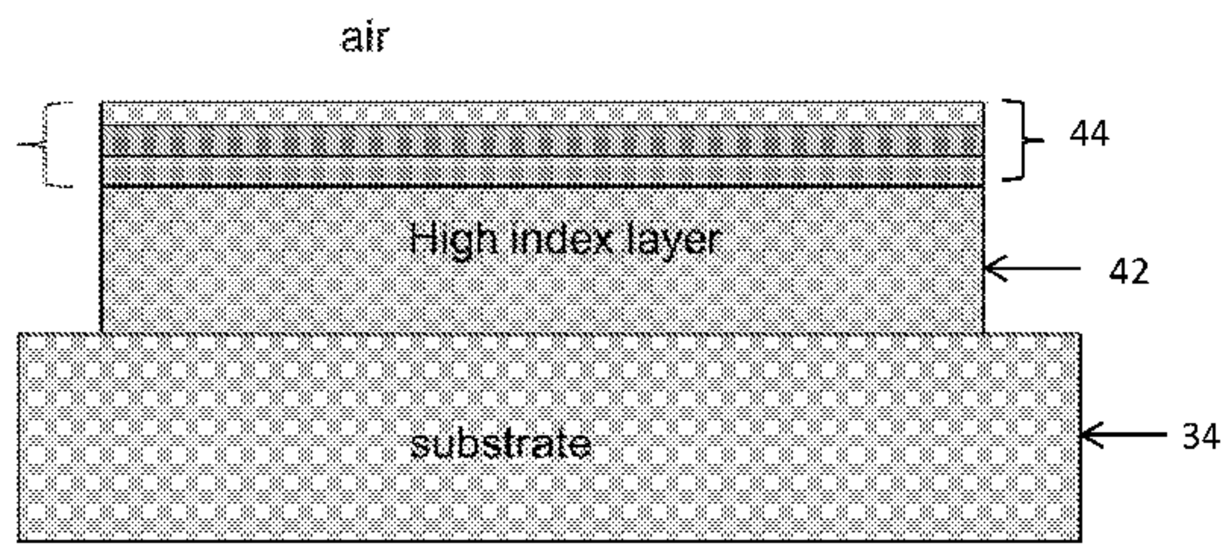


Fig. 2



(57) **Abstract:** A lightguide optical element (LOE) configured for polarization scrambling is provided. The LOE includes a transparent substrate having a first refractive index, the substrate having a pair of parallel external surfaces configured to propagate light within the LOE through total internal reflection (T!R), and a plurality of mutually parallel partially reflective internal surfaces, those being non-parallel to the pair of parallel external surfaces and configured to couple out said light to a viewer. The LOE further includes a first coating on at least one external surface of the substrate, the first coating being of a coating material having a second refractive index higher than the first refractive index; The LOE further includes an antireflective (AR) coating on at least one external surface of the substrate over the first coating.

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[Continued on next page]

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LIGHTGUIDE OPTICAL ELEMENT FOR POLARIZATION SCRAMBLING

TECHNICAL FIELD

The presently disclosed subject matter relates to a lightguide optical element, and, more particularly, to a lightguide optical element configured for polarization scrambling.

BACKGROUND

The present invention relates to light-guide compact collimating optical devices (LCCDs) and to optical systems which include one or more of these devices. The term "light-guide" refers to any light-transmitting body, preferably light-transmitting, solid bodies, also known as optical substrates. One of the important applications for compact optical devices is in the field of Head Mounted Displays (HMD), wherein an optical module serves both as a reflecting optical element and a combiner, in which a two-dimensional image is imaged to infinity and reflected into the eye of an observer. The image can be obtained directly from a spatial light modulator (SLM), such as a cathode ray tube (CRT), a liquid crystal display (LCD), liquid crystal on silicone (LCOS) module, an organic light emitting diode array (OLED), micro-LED a scanning source or similar devices, or indirectly, by means of a relay lens or an optical fiber bundle. The image comprises an array of elements (pixels) imaged to infinity by a collimating lens and transmitted into the eye of the viewer by means of a reflecting or partially reflecting surface acting as a combiner for non-see-through and see-through applications, respectively. Typically, a conventional, free-space optical module is used for these purposes. This optical module will be referred to herein as a Lightguide Optical Element ("LOE").

Typically, the LOE is positioned in front of the viewer's eye. A collimated beam of light rays entering the LOE is reflected between the parallel surfaces by total internal reflection ("TIR"). Coated facets partially reflect the rays towards the viewer's eye.

Typically, the light entering the LOE is either S-polarized or P-polarized. The coatings on the facets reflect light having the same polarization state. Since there is only one polarization state involved, the TIR reflection will maintain this polarization state. However, in applications where the light entering the LOE is unpolarized, every TIR reflection causes a phase shift which will change the polarization state of some of the rays. This in turn can lead to a corresponding change in the amount of light reflected by the facets, which is undesirable.

GENERAL DESCRIPTION

According to one aspect of the presently disclosed subject matter there is provided a lightguide optical element (LOE) configured for polarization scrambling including: a transparent substrate having a first refractive index, the substrate including a pair of parallel external surfaces configured to propagate light within the LOE through total internal reflection (TIR), and a plurality of mutually parallel partially reflective internal surfaces, the plurality of mutually parallel partially reflective internal surfaces being non-parallel to the pair of parallel external surfaces and configured to couple out the light to a viewer; a first coating having a thickness between 100nm and 10 microns on at least one external surface of the substrate, the first coating including a coating material having a second refractive index higher than the first refractive index; and an antireflective (AR) coating on at least one external surface of the substrate over the first coating.

In some embodiments the first coating is configured to increase a phase shift between s-polarized and p-polarized components of light incident at angles above a TIR cutoff angle for the substrate, the light having a wavelength between 400nm and 1300nm.

In some embodiments the AR coating is configured to reduce or eliminate reflections of light entering the LOE at angles of incidence between 0° and 50°.

In some embodiments the AR coating is configured to reduce reflections of light entering the LOE at predetermined angles to between 0.3% and 10% reflected light.

In some embodiments the first coating includes a high index dielectric material.

In some embodiments the first coating includes a material selected from the group consisting of TiO_2, Si_3N_4 and ZnS.

In some embodiments the AR coating includes one or more layers of at least one coating material selected from the group consisting of SiO_2, HfO_2, TiO_2, MgF_2 and Al_2O_3.

In some embodiments the AR coating includes one or more layers of at least one material having a refractive index in the range of 1.35 to 2.5.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it can be carried out in practice, embodiments will be described, by way of non-limiting examples, with reference to the accompanying drawings, in which:

Fig. 1 illustrates a generalized schematic diagram of a LOE according to the prior art;

Fig. 2 illustrates a generalized schematic diagram of an LOE according to certain embodiments of the presently disclosed subject matter;

Fig. 3 illustrates a graph showing an example of a phase shifting performance of one surface of the LOE without the polarization scrambling coating;

Fig. 4a illustrates a graph showing the high spectral peaks of RGB light;

Fig. 4b illustrates a graph showing the high spectral peaks of white light;

Fig. 5 illustrates a graph showing an example of a spectral differential phase shift performance of a polarization scrambling coating applied to a substrate;

Fig. 6 illustrates a graph showing reflective properties of an exemplary polarization scrambling coating without an AR coating at normal incidence;

Fig. 7a illustrates a graph showing an example of a differential phase shift on reflection of light reflected by an LOE surface for rays in TIR;

Fig. 7b illustrates a graph showing examples of differential phase shift on reflection for a variety of different angles in the TIR region;

Fig. 8 illustrates a graph showing an example of reflections at normal incidence with the polarization scrambling coating and AR coating;

Fig. 9 illustrates a graph showing an example of reflections of the polarization scrambling coating applied between the substrate and a metallic coating;

Fig. 10 illustrates an embodiment of display system with two waveguides; and

Fig. 11 illustrates another embodiment of an LOE according to the present invention.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those skilled in the art that the presently disclosed subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, and components have not been described in detail so as not to obscure the presently disclosed subject matter.

As used herein, the term 'phase shift' refers to the difference between the phase of the S-polarized rays and P-polarized rays.

Bearing this in mind, attention is drawn to **Fig. 1** illustrating a generalized schematic diagram of a LOE according to the prior art. The LOE comprises a substrate 34 that has a pair of parallel external surfaces 26, 27, and a non-parallel set of mutually parallel partially reflective internal surfaces ("facets") 22. The partially reflective property of facets 22 is achieved via a coating applied to the facets. Light rays 18 representing an image is coupled into the LOE and propagates within the LOE via TIR between surfaces 26, 27, and are eventually reflected out by facets 22 towards the eye 24 of a viewer.

Fig. 2 illustrates a generalized schematic diagram of an LOE according to certain embodiments of the presently disclosed subject matter. In this case, the LOE is intended to receive and couple out unpolarized light. As in the prior art LOE's, the LOE of the present invention is comprised of a transparent substrate 34 having a refractive index (denoted herein as "n") higher than air. The substrate comprises a pair of parallel external surfaces 26, 27 configured to propagate light within the LOE through TIR. Substrate 34 further comprises a plurality of mutually parallel partially reflective internal surfaces ("facets") 22 configured to couple out the light to a viewer. The facets are non-parallel to the external surfaces 26, 27. For example, they may be inclined relative to the pair of external surfaces.

The LOE further includes a polarization scrambling coating 42 applied to at least one of surfaces 26, 27. Coating 42 is comprised of a coating material having a refractive index, which is higher than the first refractive index of substrate 34. The polarization scrambling coating 42 is applied to at least one of the external surfaces 26, 27, or a portion thereof, in a thickness greater than 100nm and up to about 10 microns. In some cases, the polarization scrambling coating 42 can be applied to both parallel external surfaces. The polarization scrambling coating 42 applied to the external surfaces of the substrate increases the phase difference slope between the S-polarized and P-polarized light rays entering the substrate and reflecting off the inside of the external coated surface. This is for angles of incidence above the Total Internal Reflection (TIR) angle. The phase difference slope is the amount of change of the phase shift difference for a small change of the wavelength.

Polarization scrambling coating 42 can be selected according to predetermined design requirements based on the expected range of wavelengths of light entering the LOE and the expected range of angles at which the light will enter, for instance angles in the TIR region above 42° for BK7 glass. After a few reflections, the S-polarized light and P-polarized light propagating within the LOE will become greatly phase shifted with respect to one another, essentially maintaining the light rays' unpolarized state. According to this invention, the facets 22 within the LOE are also coated with a partially reflective coating designed for unpolarized light. These coated facets reflect the unpolarized light towards the viewer as designed.

In exemplary embodiments, polarization scrambling coating 42 is applied in a thickness of between 300nm – 10000nm, and more preferably between 300nm – 5000nm, and even more preferably between 300nm – 1000nm.

Preferably, polarization scrambling coating 42 is comprised of a high index dielectric material such as TiO_2 ($n \approx 2.2$-2.45), Si_3N_4, ($n \approx 2.0$), ZnS ($n \approx 2.2$-2.4) or suitable equivalents. By "high index" it is meant a refractive index higher than of the substrate and preferably at least 2. Preferably, coating 42 is configured to increase the phase shift slope of light having a wavelength between 400nm and 1300nm, and more preferably between 400nm and 750nm, upon reflection off of an external surface of the substrate.

The LOE further includes an anti-reflective (AR) coating 44 applied to at least one external surface of the substrate on top of coating 42. The AR coating 44 applied on top of the polarization scrambling coating 42 reduces or eliminates reflections of light entering the LOE at given angles, thus providing for high transmittance of these light rays and allowing the viewer to see the outside world through the LOE. In an exemplary embodiment, the AR coating is configured to reduce or eliminate reflections of light rays hitting the surface at substantially "normal" incidence angles, e.g. angles in the range of 0°- 50°. Preferably the AR coating reduces reflections of light entering the LOE at predetermined angles to between 0.3% and 10% reflected light.

It should be noted that the polarization scrambling coating 42 increases the reflections of the substrate at normal incidence from about 5% (for a substrate with $n = 1.6$) to about 18% average in the visible spectrum (430nm-660nm). Thus, the AR coating 44 is required to reduce the reflection and also to maintain the depolarization properties induced by the polarization scrambling coating 42. These requirements increase the design complexity of the AR coating 44.

Preferably, AR coating 44 is comprised of layers of coating materials having a refractive index in the range of 1.35 to 2.5. Preferably, the coating includes one or more high refractive index materials, one or more low refractive index materials, and one or more medium (i.e. between the high and the low) refractive index materials. In exemplary embodiments, AR coating 44 can be comprised of layers of one or more of SiO_2 ($n \approx 1.45$-1.47), HfO_2 ($n \approx 2.0$-2.1), TiO_2 ($n \approx 2.2$-2.45), MgF_2 ($n \approx 1.35$-1.37) and/or Al_2O_3 ($n \approx 1.63$-1.68).

It should be noted that Fig. 2 is not drawn to scale, and in reality the thickness of substrate 34 is typically several orders of magnitude greater than that of coatings 42, 44.

Fig. 3 illustrates a graph showing the phase shift performance of an LOE without the polarization scrambling coating. In this case, the LOE is made from of S-TIM8 glass ($n \approx 1.596$) without coating 42 applied to the external surfaces. As shown, the phase shift is nearly constant for all wavelengths in the visible spectrum. This is undesirable, as will be described below.

Typically, the light entering the LOE is either from a RGB LED or white LED. **Fig. 4a** illustrates a graph showing the high spectral peaks of RGB light, where the phase shift slope enhancements should preferably occur. **Fig. 4b** illustrates a graph showing the high spectral peaks of white light, where the phase shift slope enhancements should preferably occur.

Fig. 5 illustrates a graph showing an example of the phase shift caused by polarization scrambling coating 42 applied to a substrate in reference to the spectral peaks of a RGB LED light. In this case, the coating 42 is comprised of TiO_2, and was applied to a substrate 34 made of S-TIM8 glass. **Fig. 5** shows the results of two different thicknesses of coating 42, i.e. 300nm and 1000nm, respectively. As shown in **Fig. 5**, as the thickness of the layer is increased, the slope of the phase change in the visible wavelengths becomes larger. The spectral areas where the highest depolarization and slope should take place are indicated by dashed squares, and correspond to the spectral peaks of RGB LED.

As shown in **Fig. 5**, a small change in the wavelength of the light entering the LOE produces a large change in the phase shift. This is compared to the spectral range of the LED emission that illuminates the system. The polarization scrambling coating 42 causes different degrees of phase shift to parts of the narrow spectral peaks (at ≈480nm, ≈580nm and ≈640nm for the RGB LED, and ≈443nm for the white LED). Since the human eye integrates the intensity of the light of close wavelengths, this effect is comparable to viewing unpolarized light. The depolarization after the reflection is partial. Since the light is reflected by the external surfaces multiple times before being reflected by the facets 22, the accumulated depolarization of the light rays is relatively high.

Fig. 6 illustrates a graph showing reflective properties of an exemplary polarization scrambling coating 42 without an AR coating 44. In this case, coating 42 was applied at two different layer thicknesses, 300nm and 1000nm, respectively. As shown, coating 42 tends to be highly reflective (average of about 20% per side in the visible wavelengths), causing undesirable attenuation of the view of the outside world through the LOE.

Fig. 7a illustrates a graph showing an example of a differential phase shift on reflection of light entering a LOE of the present invention. In this case, the substrate is coated with a polarization scrambling coating 42 comprised of a thick TiO_2 layer, and an AR coating 44 on top of the polarization scrambling coating. The graph shows differential phase shift on reflection of light entering the LOE at angles of incidence of 55 degrees, in the visible wavelengths, for two different thicknesses of coating 42, i.e. 300nm and 1000nm, respectively.

Fig. 7b illustrates a graph showing the phase shift on reflection using the same coatings as in **Fig. 7a**, with coating 42 applied in a thickness of 1000nm, for a variety of different angles in the TIR region.

Fig. 8 illustrates reflections at normal incidence of a coating of consisting of layers of coating 42 (300nm and 1000nm TiO2 layer thicknesses) and coating 44 as in **Fig. 7a** at different wavelengths in the visible spectrum. As shown in **Fig. 8**, this coating performs as an AR coating at small angles, where it is apparent that the reflection is greatly reduced compared to **Fig. 6** (from about 18% average in the visible spectrum to about 4%). Using different designs and layer material this reflection can be reduced even lower.

It should be noted that the thickness of coating 42 need not be identical for both external surfaces. Rather, different thicknesses of coating 42 could be applied to the different surfaces in in order to give each side of the LOE different slopes of phase change for any spectral region. For example if on one side the LOE has a small slope of phase change for a certain wavelength, the coating on the other side may randomly fall on a large slope of phase change, where the accumulated phase shift will be large.

Needless to say, if an incoming beam of light is polarized parallel or perpendicular to the facets 22, the coating 42 will have no effect on the phase of the beam.

As stated above, the polarization scrambling coating 42 can be applied to only a portion of one or both external surfaces, instead of the entire surface.

In some cases, it may be desirable for the LOE to be coated on one external surface, or a portion thereof, with a metallic coating. In that case, the polarization scrambling coating 42 can be added between the substrate and the metallic layer, which will increase the phase shift change over the spectral region.

Fig. 9 illustrates a graph showing an example of reflections of the polarization scrambling coating 42 applied between the substrate and a metallic coating. The graph shows reflections of light at a 55° angle of incidence, at different wavelengths in the visible spectrum. The graph demonstrates the phase shift slopes without the polarization scrambling coating 42, as well as with layer 42 at different thicknesses, 300nm and 1000nm.

It should be noted that in some cases, the rays entering the LOE may not be in the same plane of the drawing, i.e. entering the LOE at another three dimensional angle. In this case even if the beam is polarized, it will not be polarized in reference to the TIR planes. Therefore, it will change the polarization state of the reflected beam and can be treated as unpolarized light.

Fig. 10 illustrates a display system having two LOEs, in which the beam is reflected from one LOE at an arbitrary angle to the second LOE. This reflection introduces a phase shift that will therefore change the polarization state of the beam so it will not be polarized upon reflection from the facets. Here again, the coating 42 applied to the LOE surface will make sure that the reflection from the facets will not be dependent on the polarization state of the beam.

Fig. 11 illustrates another embodiment of an LOE according to the present invention. In this embodiment, the LOE is designed for light beams to enter at the center of the waveguide and propagate towards each opposite end. In this case, the incoming beam travels through a converging lens 6. Rays 64L and 64R pass through the LOE. The beams to the eye will either be transmitted through the center facets, or will be reflected by the central facets and travel to the side and reflected towards the eye by the other facets. Traveling from the central facets to the side facets, the rays encounter TIR from surfaces 1 and 2. Therefore, surfaces 1 and 2 should also be coated with the polarization scrambling coating 42 (and optionally one or more layers of AR coating 44) for depolarizing the beams, since the next reflecting facets are designed for unpolarized light. Here again, the addition of AR layers will increase the transmittance of surfaces 1 and 2.

It should be appreciated that embodiments of the presently described LOE can be implemented in a large number of imaging applications, such as head-mounted displays (HMDs) and head-up displays (HUDs), cellular phones, compact displays, 3-D displays, compact beam expanders, as well as non-imaging applications, such as flat-panel indicators, compact illuminators and scanners.

It is to be understood that the invention is not limited in its application to the details set forth in the description contained herein or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Hence, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for designing other structures, methods, and systems for carrying out the several purposes of the presently disclosed subject matter.

CLAIMS

1. A lightguide optical element (LOE) configured for polarization scrambling comprising:

a transparent substrate having a first refractive index, the substrate comprising a pair of parallel external surfaces configured to propagate light within said LOE through total internal reflection (TIR), and a plurality of mutually parallel partially reflective internal surfaces, said plurality of mutually parallel partially reflective internal surfaces being non-parallel to the pair of parallel external surfaces and configured to couple out said light to a viewer;

a first coating having a thickness between 100nm and 10 microns on at least one external surface of the substrate, the first coating comprising a coating material having a second refractive index higher than said first refractive index; and

an antireflective (AR) coating on at least one external surface of the substrate over said first coating.

2. The LOE of claim 1, wherein the first coating is configured to increase a phase shift between s-polarized and p-polarized components of light incident at angles of above TIR having a wavelength between 400nm and 1300nm.

3. The LOE of claim 1, wherein said AR coating is configured to reduce or eliminate reflections of light entering the LOE at angles of incidence between 0° and 50°.

4. The LOE of claim 1, wherein said AR coating is configured to reduce reflections of light entering the LOE at predetermined angles to between 0.3% and 10% reflected light.

5. The LOE of claim 1, wherein said first coating comprises a high index dielectric material.

6. The LOE of claim 5, wherein said first coating comprises a material selected from the group consisting of TiO_2, Si_3N_4 and ZnS.

7. The LOE of claim 1, wherein said AR coating comprises one or more layers of at least one coating material selected from the group consisting of SiO_2, HfO_2, TiO_2, MgF_2 and Al_2O_3.

8. The LOE of claim 1, wherein said AR coating comprises one or more layers of at least one material having a refractive index in the range of 1.35 to 2.5.

Fig. 1 (PRIOR ART)

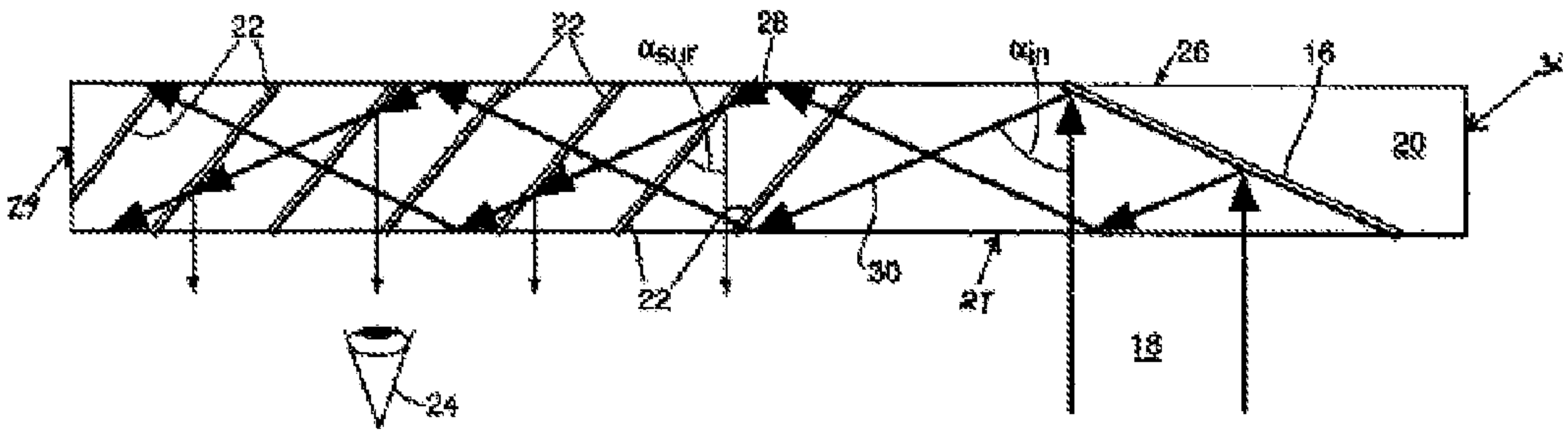


Fig. 2

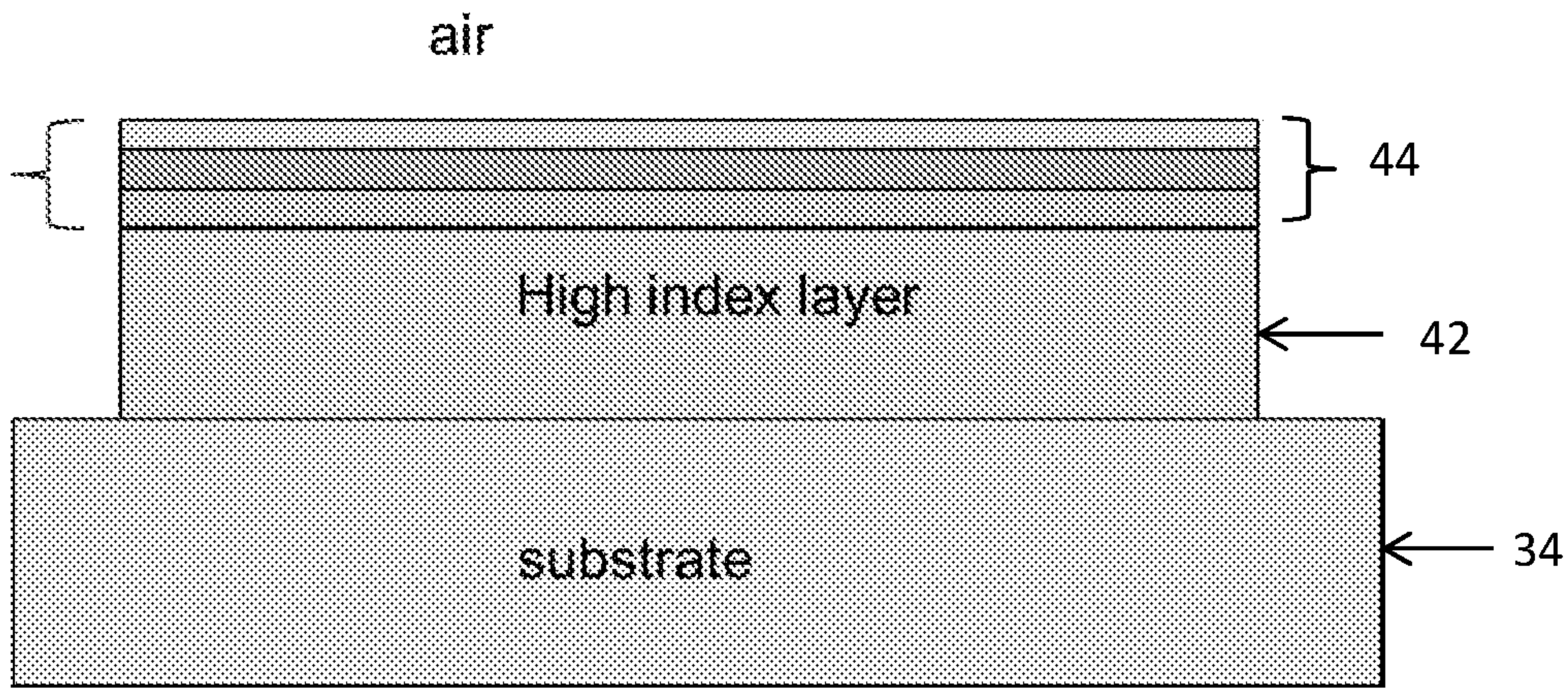


Fig. 3

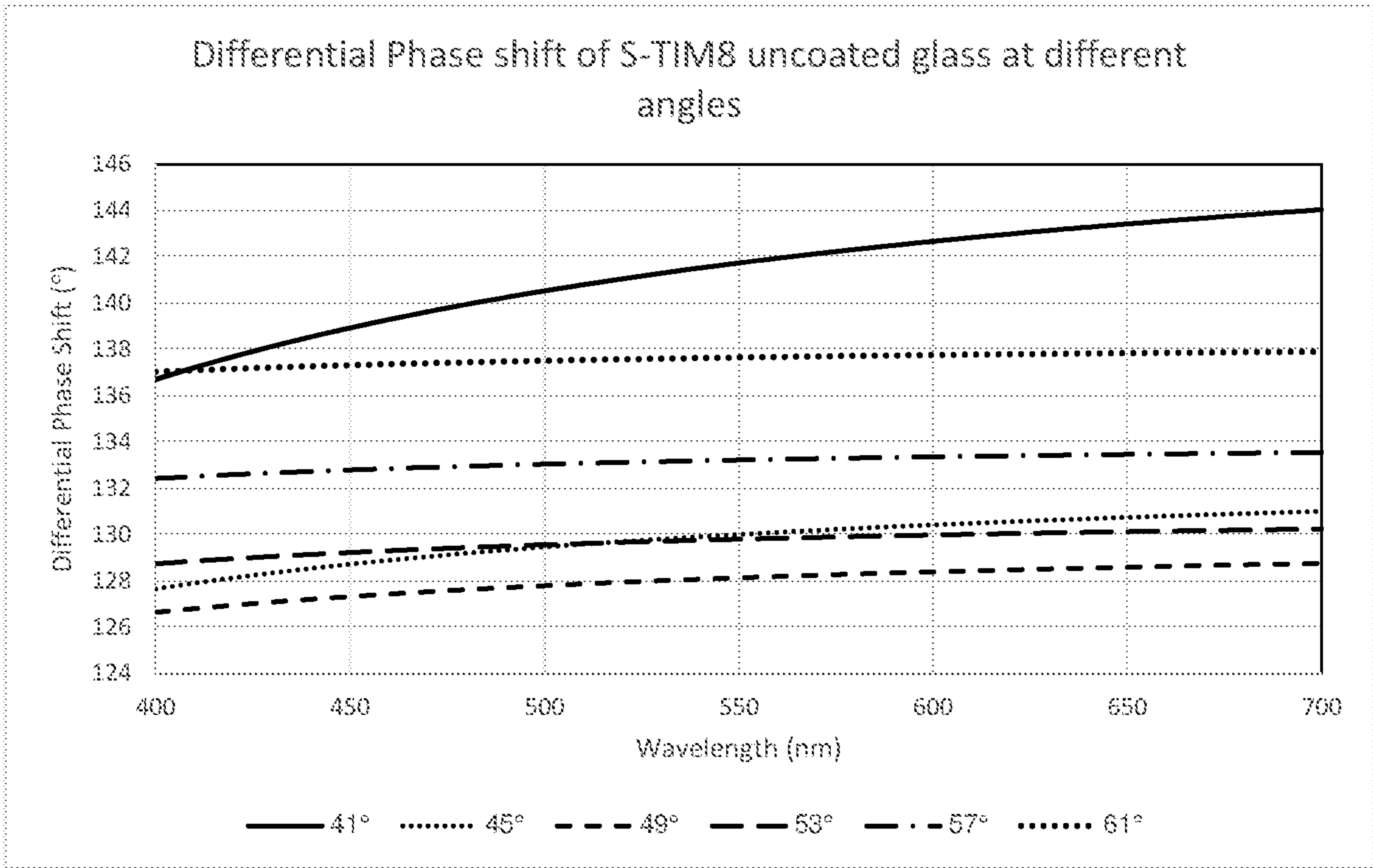

Differential Phase shift of S-TIM8 uncoated glass at different angles
146
144
142
140
138
136
134
132
130
128
126
124
Differential Phase Shift (°)
400
450
500
550
600
650
700
Wavelength (nm)
41°
45°
49°
53°
57°
61°

Fig. 4a

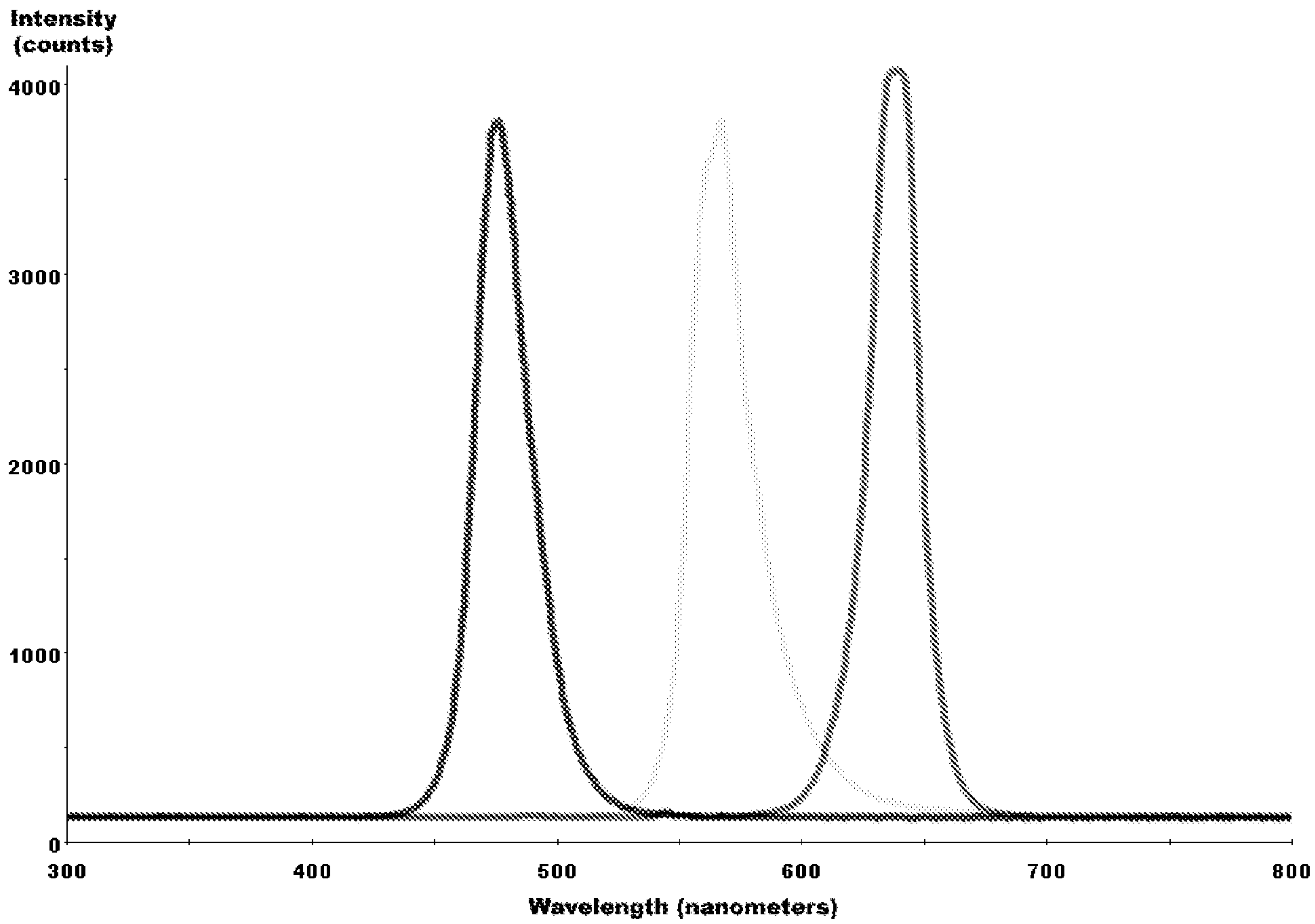

Intensity
(counts)
4000
3000
2000
1000
0
300
400
500
600
700
800
Wavelength (nanometers)

Fig. 4b

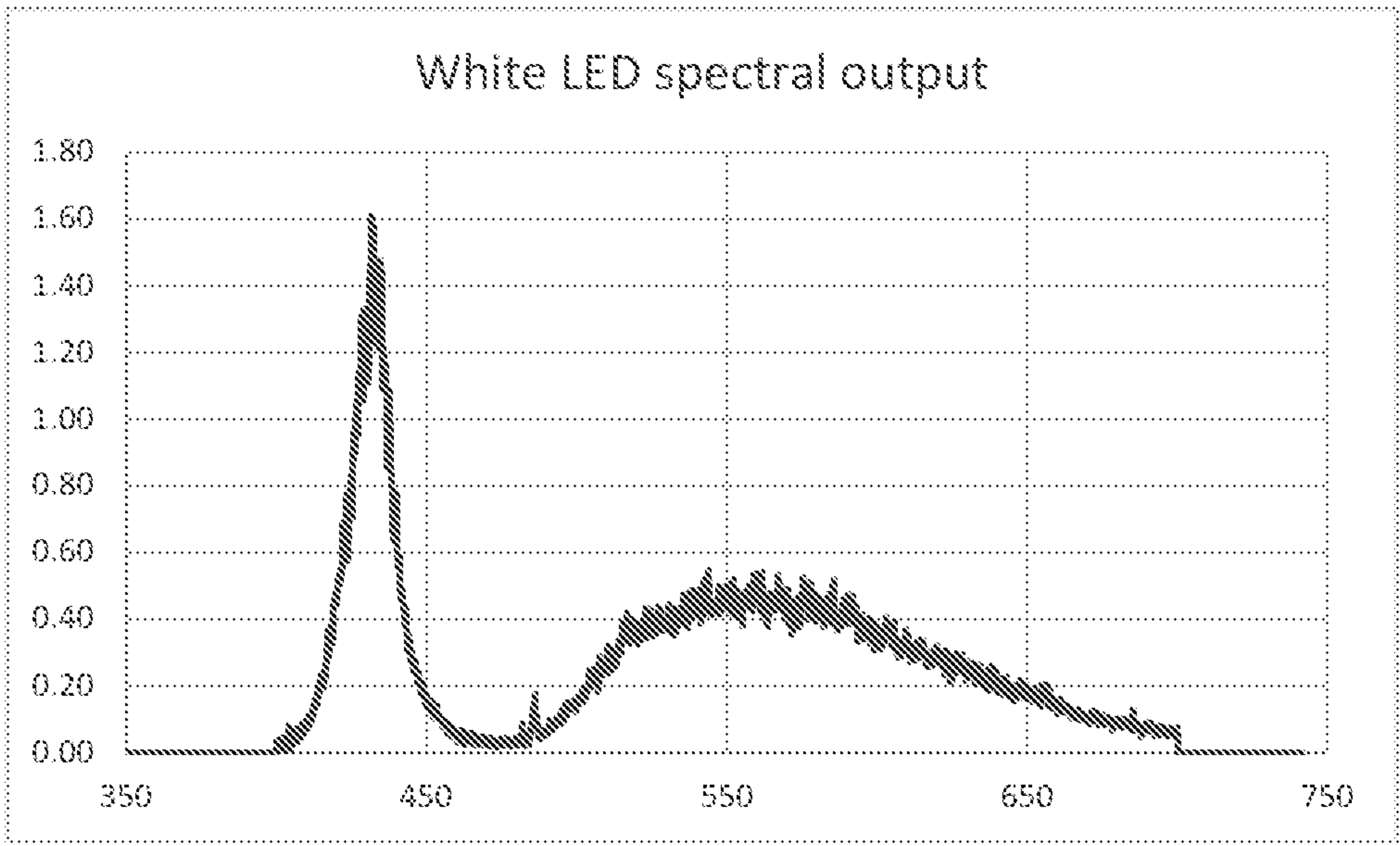

White LED spectral output
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
350
450
550
650
750

Fig. 5

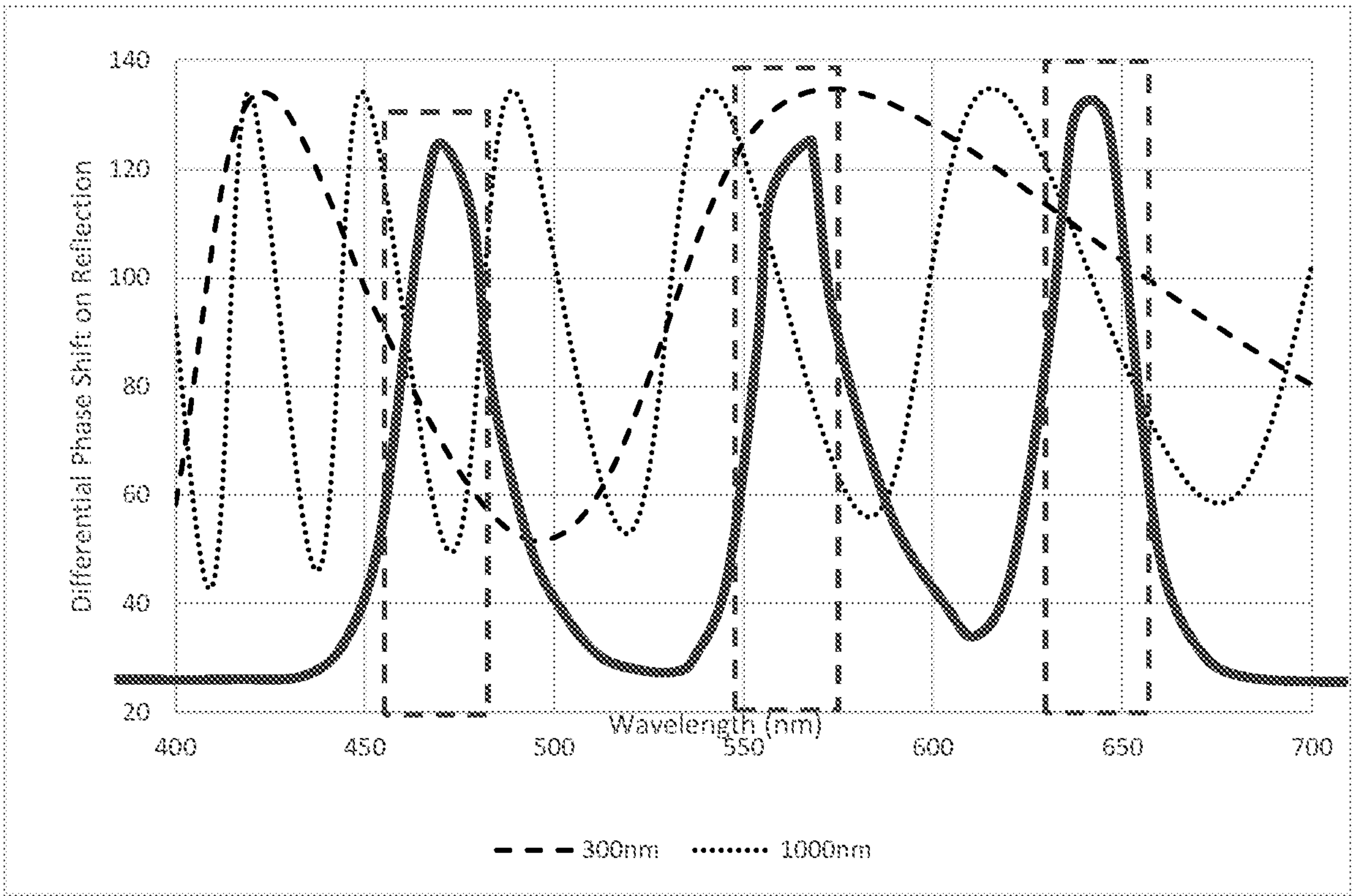

140
120
100
80
60
40
20
Differential Phase Shift on Reflection
400
450
500
550
600
650
700
Wavelength (nm)
300nm
1000nm

Fig. 6

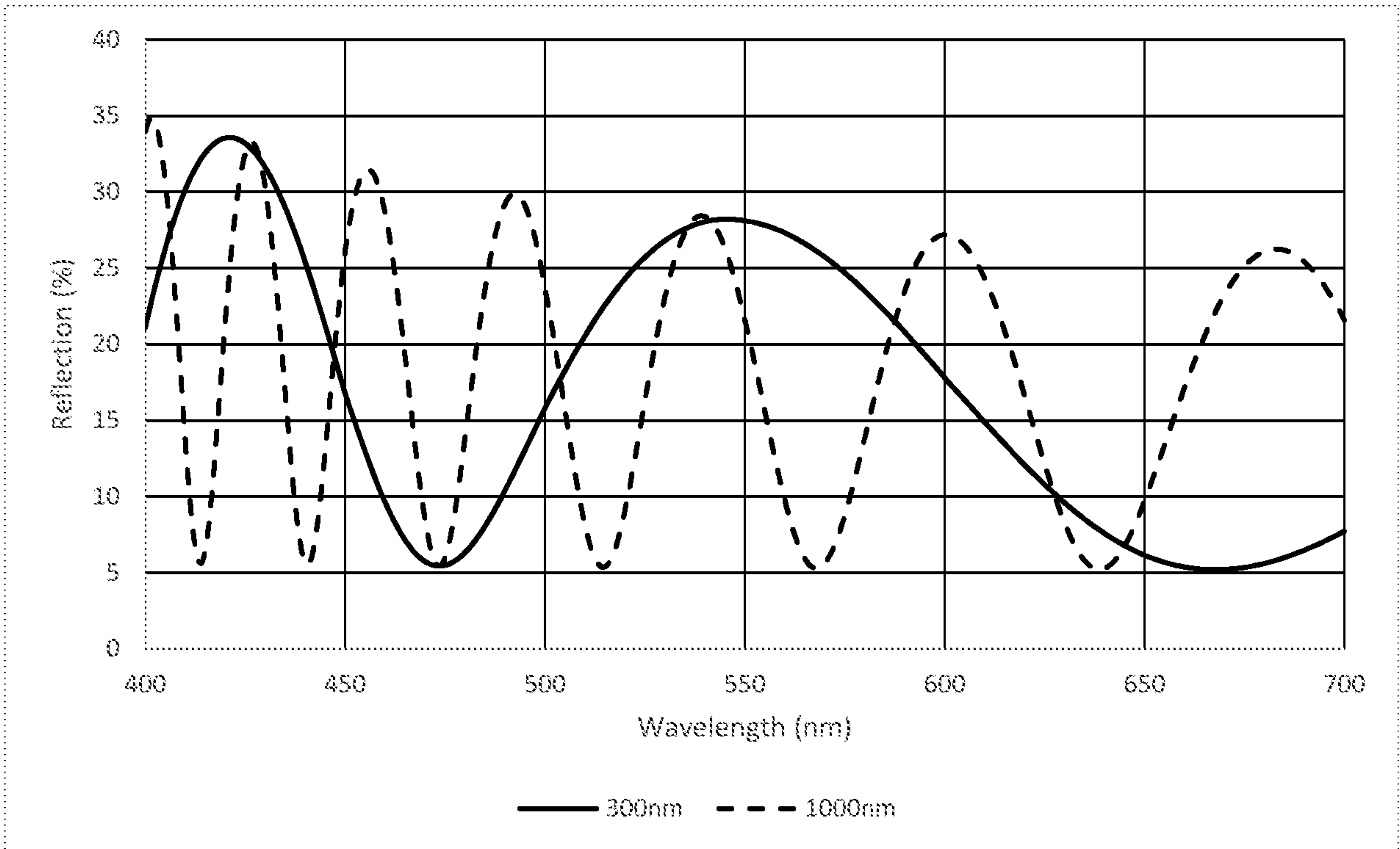

40
35
30
25
20
15
10
5
0
Reflection (%)
400
450
500
550
600
650
700
Wavelength (nm)
300nm
1000nm

Fig. 7a

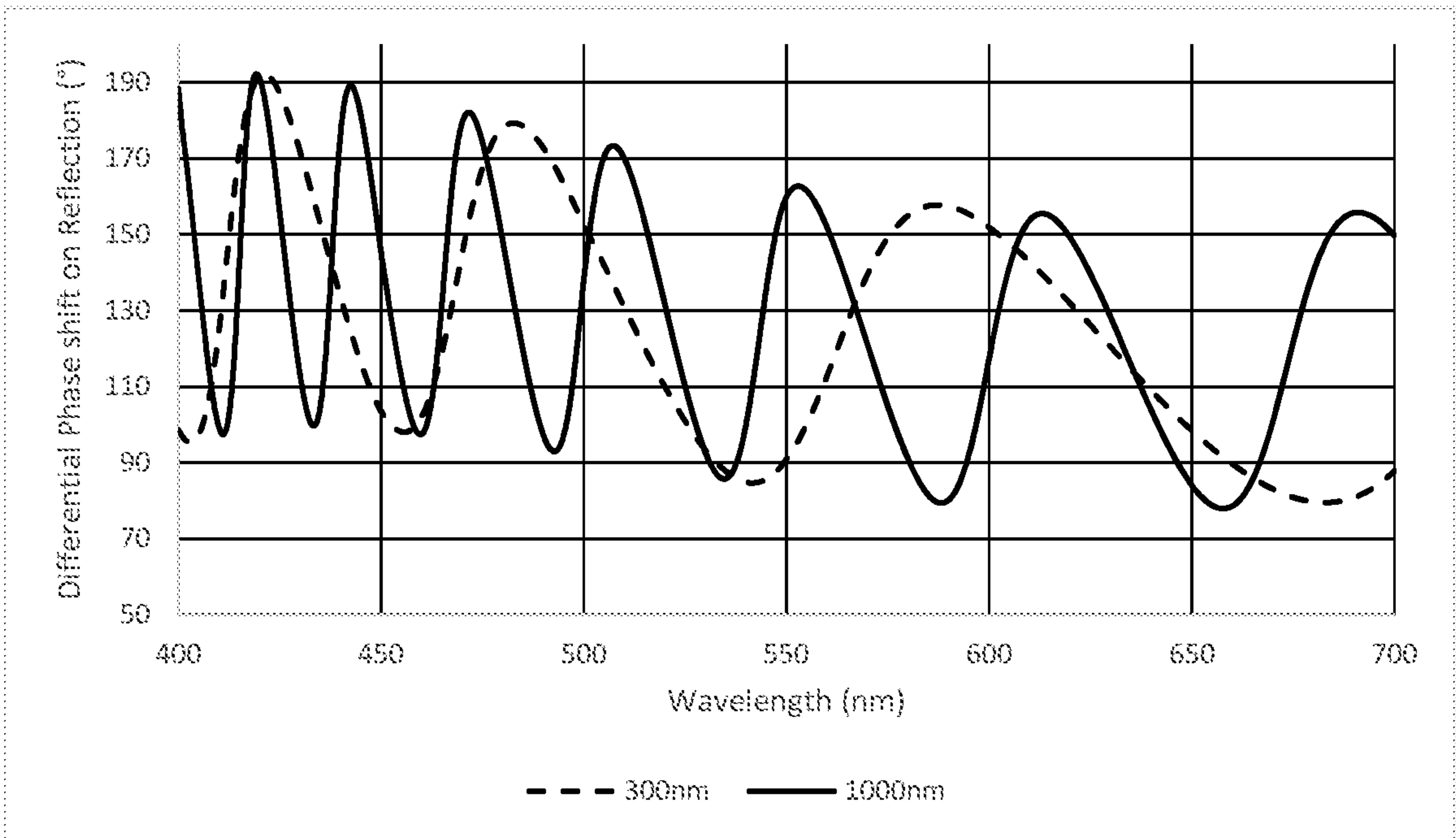

190
170
150
130
110
90
70
50
Differential Phase shift on Reflection (°)
400
450
500
550
600
650
700
Wavelength (nm)
300nm
1000nm

Fig. 7b

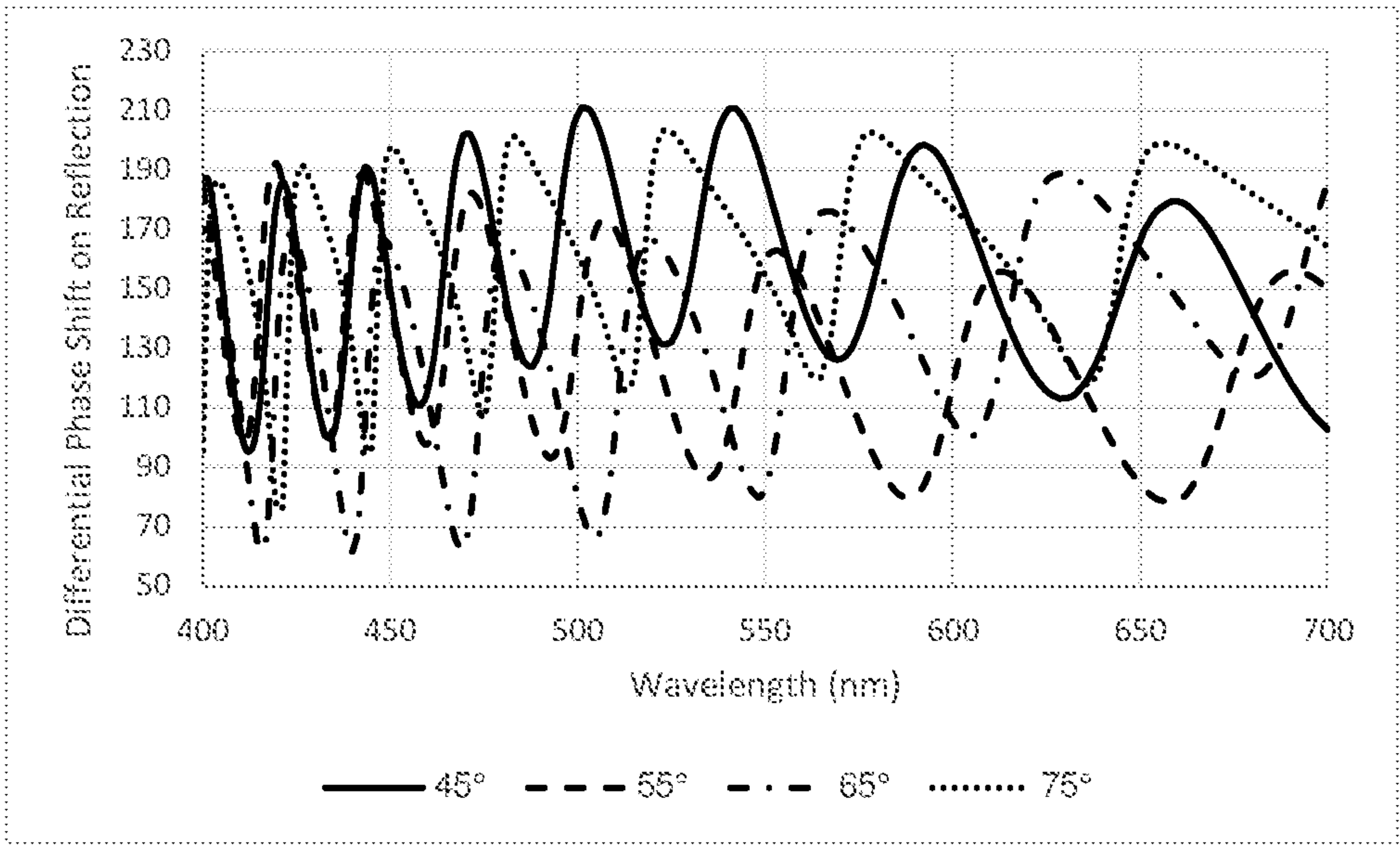

230
210
190
170
150
130
110
90
70
50
Differential Phase Shift on Reflection
400
450
500
550
600
650
700
Wavelength (nm)
45°
55°
65°
75°

Fig. 8

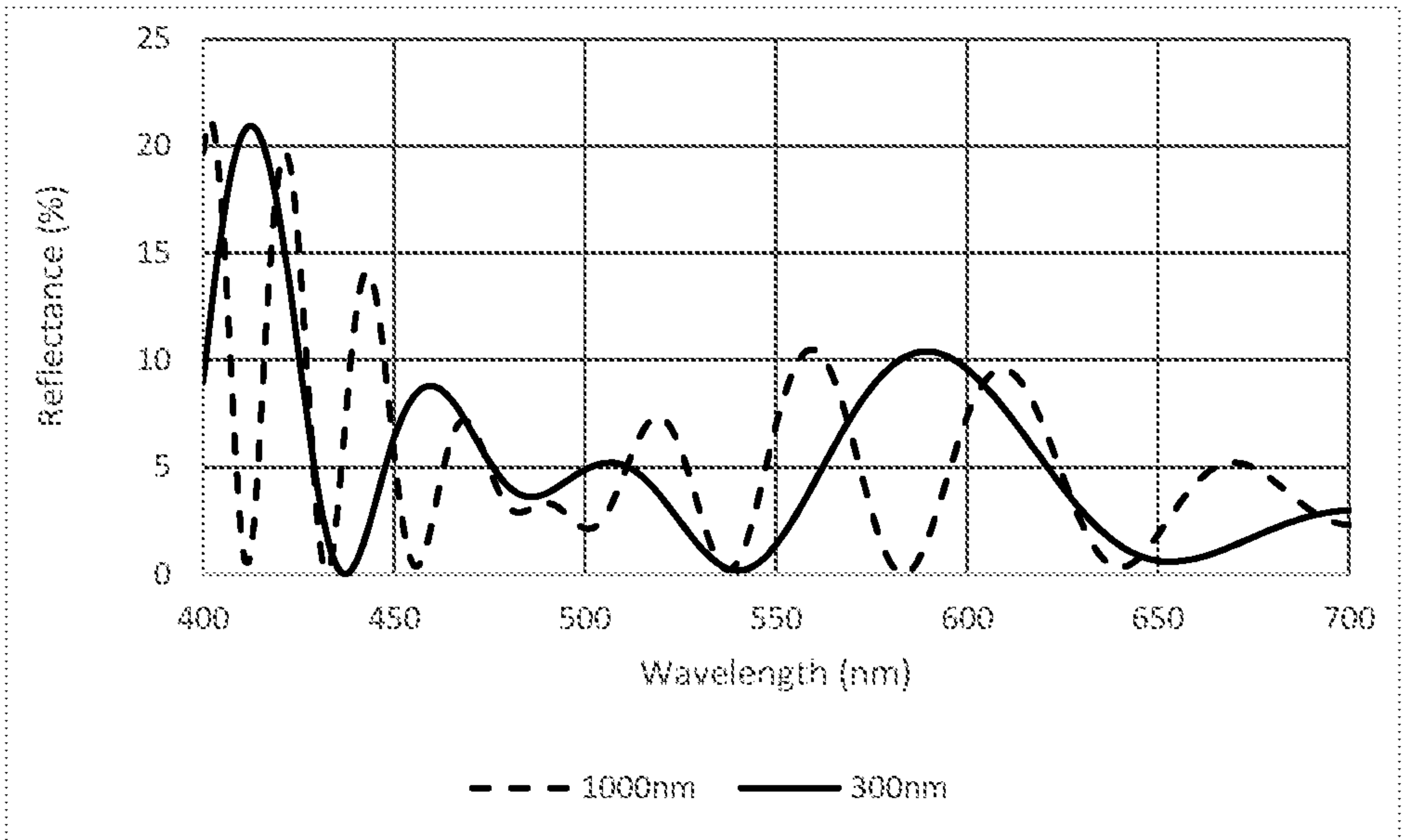

25
20
15
10
5
0
Reflectance (%)
400
450
500
550
600
650
700
Wavelength (nm)
1000nm
300nm

Fig. 9

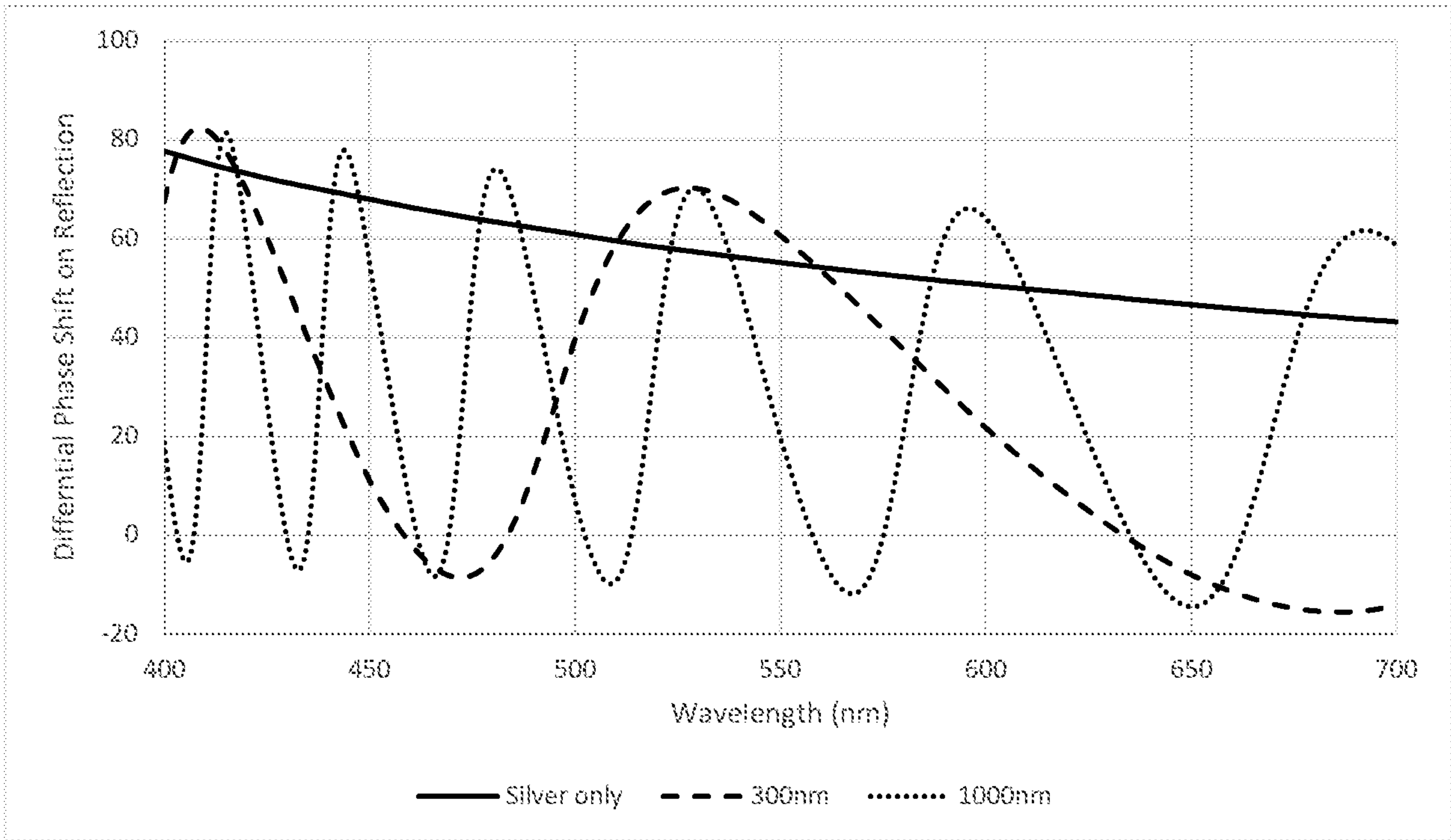

100
80
60
40
20
0
-20
Differential Phase Shift on Reflection
400
450
500
550
600
650
700
Wavelength (nm)
Silver only
300nm
1000nm

Fig. 10

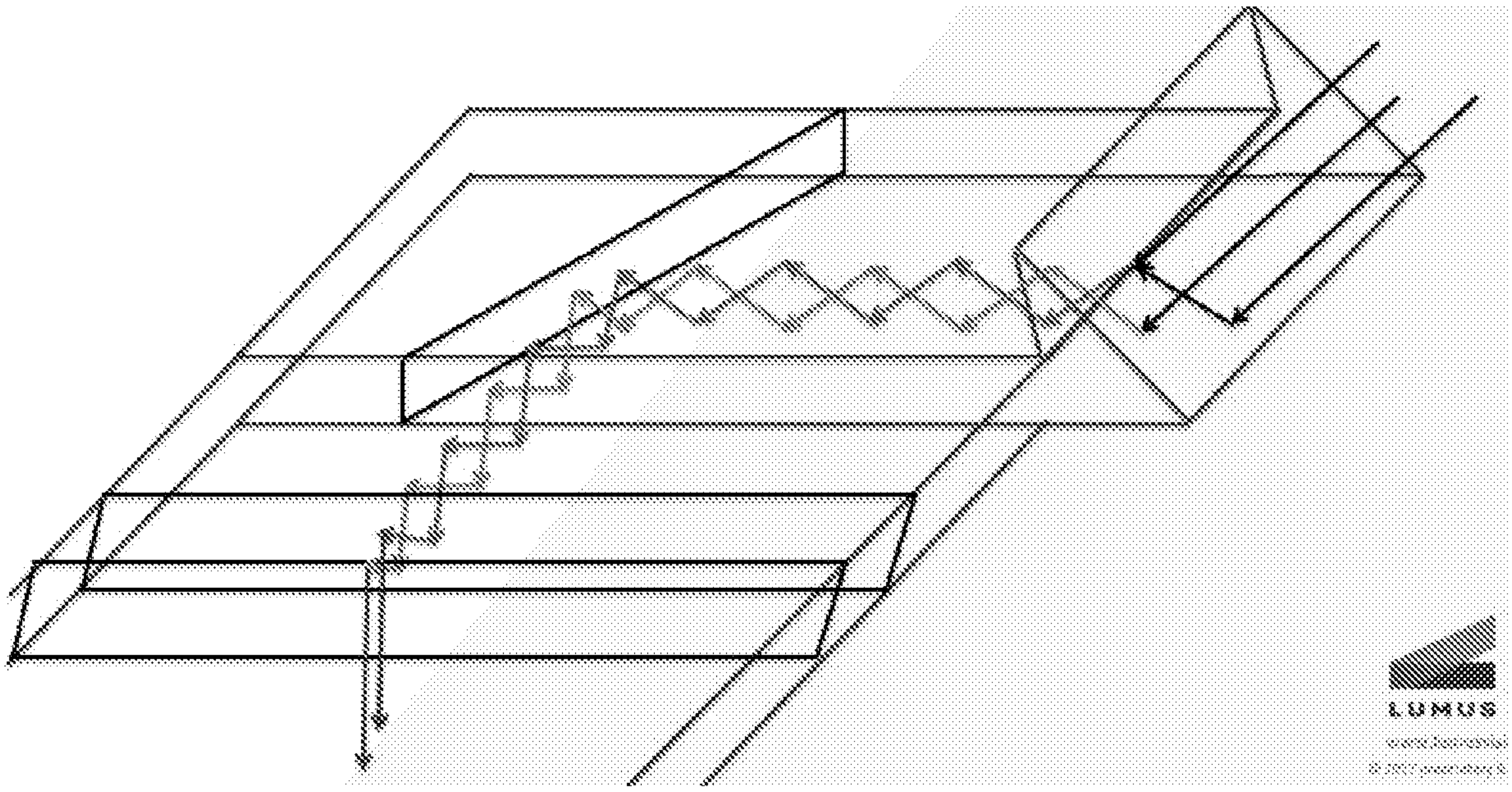
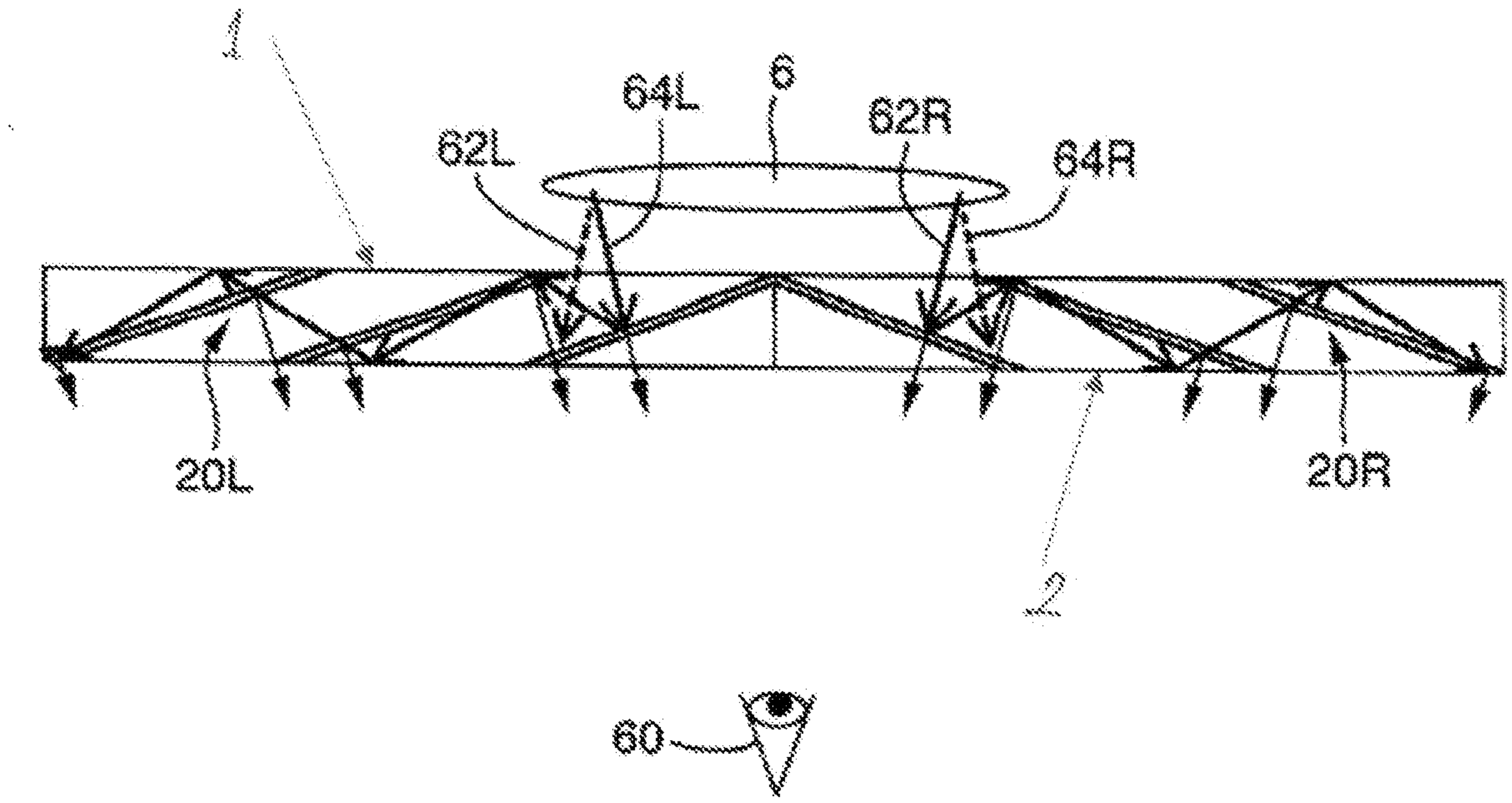


Fig. 11



INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2020/051166

A. CLASSIFICATION OF SUBJECT MATTER
IPC (20210101) G02F 1/01, G02B 6/10, G02B 27/00, G02B 27/01
CPC (20130101) G02F 1/0136, G02B 6/105, G02B 27/0081, G02B 27/01, G02F 2001/0139
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC (20210101) G02F 1/01, G02B 6/10, G02B 27/00
CPC (20190101) G02F 1/01, G02B 6/10, G02B 27/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Databases consulted: Google Patents, Google Scholar, Derwent Innovation, SIMILARI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018210202 A1 (LUMUS LTD) 26 Jul 2018 (2018/07/26) The whole document	1-8
A	US 2013250430 A1 (ROBBINS STEVE ; BOHN DAVID D ; MICROSOFT TECHNOLOGY LICENSING) 26 Sep 2013 (2013/09/26) The whole document	1-8
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A	US 2018292592 A1 (LUMUS LTD) 11 Oct 2018 (2018/10/11) The whole document	1-8

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 Jan 2021	13 Jan 2021

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2020/051166

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