
Optical filters for plasma-display panels using organic dyes and conductive mesh layers by using a roll-to-roll etching process

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Abstract — Optical filters with a high shielding capability against electromagnetic (EM) radiation for plasma-display panels (PDPs) have been studied. We developed optical filters with high conductivity by utilizing a copper-mesh layer, which was processed by using roll-to-roll photolithography and roll-to-roll etching. The copper-mesh layer has a cross-striped pattern with a surface resistance of $0.05 \Omega/\square$ and an opening ratio of approximately 93%. In combination with the copper-mesh layer, organic dyes were applied to reduce the PDPs unfavorable emissions, such as near-infrared light, and to control the transmission properties to improve the PDPs picture quality.

Keywords — PDP, optical filter, EM-radiation shielding, shielding, copper mesh, mesh layer, roll-to-roll process, photolithography, wet etching, organic dye, NIR, picture quality.

1 Introduction

PDPs have been considered to be one of the most promising thin flat-panel color displays for large-area screen applications, and the market for PDP TVs has spread to consumer use. However, PDPs have some operating-principle challenges that need to be addressed.

First, PDP modules emit strong EM radiation. Since EM radiation from electronic equipment is restricted by legal regulations such as the one from the Federal Communications Commission (FCC), EM radiation from PDP modules must be shielded to meet these regulations. We reported optical filters that use conductive sputtered multilayered coatings^{1,2} to be mounted in front of PDP modules. However, since some PDP modules emit high EM radiation, combinations of the sputtered multilayered coatings with a surface resistance of $1.2\text{--}2.4 \Omega/\square$ and some PDP modules cannot meet some of the regulations, especially the ones for consumer use which generally require a 10-dB-lower intensity level of EM radiation than that for industrial use.

Second, PDPs also emit intense near-infrared light (NIR) which sometimes causes malfunctions of the apparatus that operate in the NIR,^{1,3} for instance, NIR communicating devices (working band, 850–900 nm) standardized by the Infrared Data Association (IrDA) and some remote-controlled systems (800–1000 nm) such as TVs and VTRs. Therefore, NIR from PDPs should be reduced in order to avoid problems in practical use.

Third, picture qualities such as PDP color reproducibility and contrast usually need to be improved. In this paper, we describe, in detail, PDP optical filters using organic dyes and copper-mesh layers with high conductivity.

2 Preparation of copper-mesh laminates

To begin with, in order to obtain optical filters with high EM-radiation shielding, we chose a copper-mesh layer with a film substrate made of polyethylene terephthalate (PET) for the conductive layer of the optical filters. Copper not only has a high electrical conductivity, but is easily processed by etching. PET film, among all of the polymeric films, is the most suitable for our purpose because of its high mechanical strength, high transparency, and high heat and chemical resistance.

The Cu-mesh layer, which has a cross-striped pattern of Cu foil by a photolithography and etching process, can have a much lower surface resistance than sputtered multilayered coatings used for conventional optical filters.^{1,2} Sputtered multilayered coatings do not have a low surface resistance, *e.g.*, less than $0.9 \Omega/\square$, without increasing its reflection and decreasing its transmission. The Cu-mesh layer can also have a lower surface resistance and a finer line width than a metal-plated fibrous mesh that generally has a surface resistance of about $0.5 \Omega/\square$ and a line width of 20–30 μm . The fine copper-mesh layer can have a high opening ratio, *i.e.*, a high light transmittance.

Figure 1 shows a magnified picture of an example of the Cu-mesh layer obtained, which has a line width of ca. 10 μm and has a line pitch of ca. 300 μm , *i.e.*, an opening ratio of approximately 93%. The measured surface resistance was $0.05 \Omega/\square$.

Cu-mesh laminates comprising the Cu-mesh layer, PET film, and adhesive layer were obtained by using a continuous roll-to-roll photolithography and etching process, which resulted in high productivity. Figure 2 shows the schematic flow chart of the process we applied.

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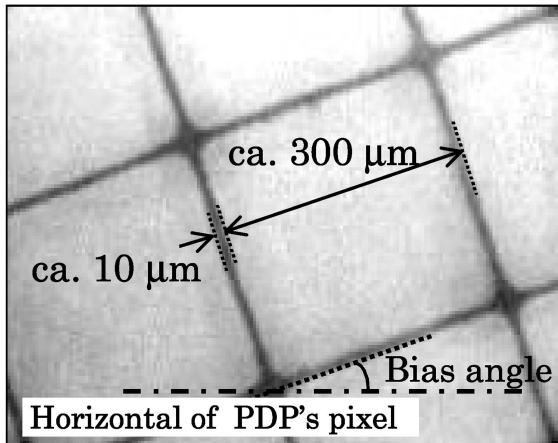


FIGURE 1 — Magnified schematic of the Cu-mesh layer with an opening ratio of ca. 93% and with a measured surface resistance of 0.05 Ω/h . The bias angle, a line at which the mesh pattern crosses with a horizontal line of the PDP pixel pattern was determined to be appropriate for the PDP.

In the process (1), a roll (i) of PET film with a thickness of 100 μm and a roll (ii) of electrodeposited Cu foil with a thickness of 10 μm were prepared, and (1a) the PET film and the Cu foil were continuously laminated with a polyester adhesive (iii). Here, the Cu foil had a blackened surface on the viewer's side of the optical filters to prevent Cu-metallic reflection that lowers viewability, and also had anti-corrosion treated surfaces. Then, a roll (iv) of dry-film photoresist was prepared, and (1b) the dry-film photoresist was continuously laminated on the Cu-foil layer.

In the process (2), exposure by ultraviolet light through a photomask was intermittently processed. In the photomask, a cross-striped pattern was described in order to obtain the Cu-mesh layer with a mesh pattern with an expected line width, an expected line pitch, and an appropriate bias angle. As shown in Fig. 2, the patterned area was limited so that a non-patterned area would remain. The bias angle, an angle at which a line of mesh pattern crosses with a horizontal of PDP pixels as shown in Fig. 1, was determined to be appropriate for the PDP for fear that a moiré phenomenon might appear due to an interference of the mesh pattern and PDP's subpixel pattern.

In the process (3), (3a) development by sodium carbonic solution, (3b) wet etching using sodium hydroxide solution, (3c) removal of the photoresist, and (3d) washing by hot water were continuously processed in this order. As shown in Fig. 2, Cu-mesh laminates with a non-etched area was obtained.

In the process (4), an acrylic transparent adhesive (v) with a thickness of ca. 25 μm was continuously coated on the PET surface of the Cu-mesh laminate.

3 Fabrications of optical filter using copper-mesh laminates

There are two possible ways to mount optical filters in PDP TVs. One is to attach an optical filter directly onto the front-

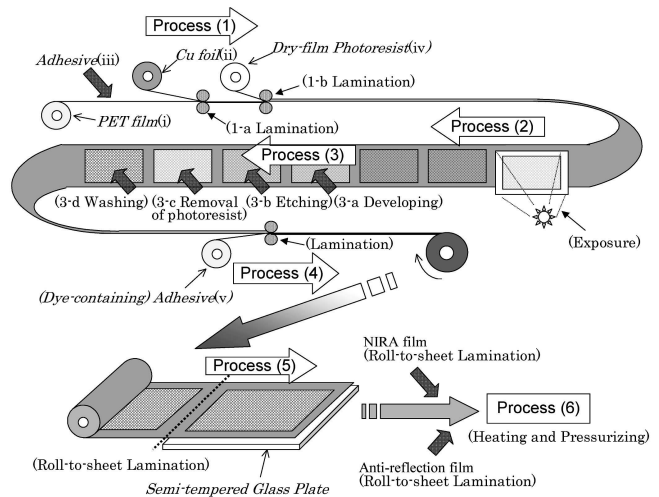


FIGURE 2 — Schematic process flow chart of Cu-mesh laminates and optical filters. Cu-mesh laminates were obtained by a continuous roll-to-roll photolithography and etching process indicated by (1)–(3). Optical filters were fabricated by a roll-to-roll lamination process (4) of a (dye-containing) adhesive and a roll-to-sheet lamination process (5) of Cu-mesh laminates and other films on a semi-tempered glass substrate, and by a heating and pressurizing treatment.

panel surface of a PDP with a transparent adhesive.⁴ The other is to mount an optical filter having a transparent rigid supporting plate in front of a PDP. For the present, the latter case is preferable since the PDP, which is not mechanically strong, should be sufficiently protected by the optical filter. As a supporting plate, thermal (semi-) tempered glass with a thickness of 2.5–3.2 mm is preferable. Because an optical filter using a plastic plate such as polymethyl methacrylate (PMMA) sometimes warps, due to expansion by heat and/or moisture absorption when mounted in a PDP TV.

Furthermore, various functions such as anti-reflection, anti-glare, anti-electrostatic, wear-proof, and print-free, *etc.* are required for optical filters.⁵ Transparent polymeric films with the above functions are used in optical filters.

Figure 3 shows a schematic cross-sectional view of an example of the optical filter with a frame-shaped black print and a bus bar formed in the peripheral region. The purpose of the bus bar is to electrically connect a conductive layer of the optical filter to the electrical ground of a PDP TV in order to make an electric charge induced by the absorption of EM radiation at the conductive layer lead to the ground effectively. The non-patterned area of the Cu-mesh layer as shown in Fig. 2 can be used for this bus bar. In the process (5) shown in Fig. 2, we applied a roll-to-sheet process for laminating Cu-mesh laminates on a semi-tempered glass substrate. Utilizing a laminator that we developed, with optical sensing of a boundary between the patterned area and the non-patterned area of the Cu-mesh layer, the Cu-mesh laminate was sequentially laminated on the substrate so that the patterned area could be centered on the substrate and the non-patterned area could be formed on the peripheral region of the substrate.

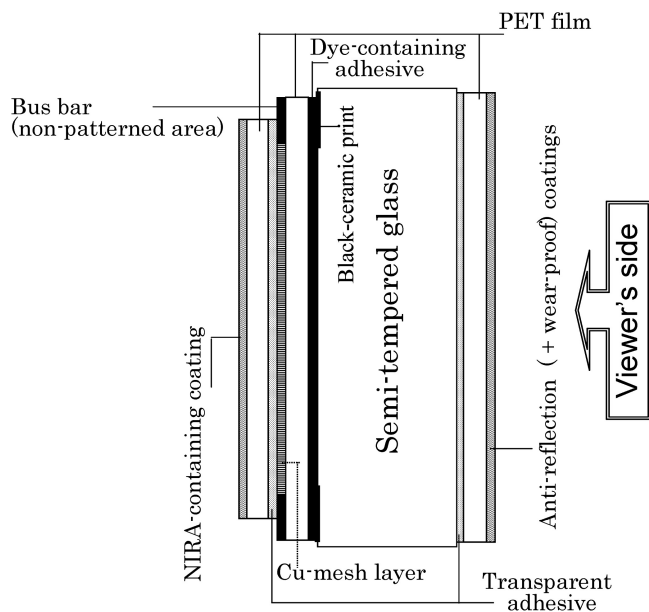


FIGURE 3 — Schematic cross-sectional view of an optical filter using a Cu-mesh layer. This optical filter has frame-shaped black print and a bus bar in the peripheral region.

Other polymeric films with various functions were laminated on the substrate with the Cu-mesh layer by a roll-to-sheet process (without the above-described sensing), too.

A Cu-mesh laminate has a very low transparency owing to its high visible-light transmission haze of ca. 10%. This high haze is due to the rough surface of the adhesive layer that remained after removal of Cu foil. The rough surface of the adhesive is caused by transcription of the Cu-foil roughness, and it appears after removal of Cu foil by etching. Therefore, the transparency of a Cu-mesh laminate needs to be cleared for optical-filter use by lowering the transmission haze of the Cu-mesh laminate smooths the rough surface of the adhesive layer by coating or laminating a transparent material with a similar refractive index.

Because of the transparent material, an acrylic adhesive with which a polymeric film laminated on the mesh-patterned layer is applicable. However, because lamination cannot make the transmission haze of the laminate worse (for example, about 25%) because of (micro) air bubbles that are involved in laminating. Air bubbles exist at the surface of the Cu-mesh laminate where bumps of the mesh pattern with a height of ca. 10 μm and where the rough surface of the adhesive layer are. Because lamination cannot make the acrylic adhesive adhere to the surface of the Cu-mesh laminate thoroughly to smooth the rough surface of the adhesive layer.

In order to make the acrylic adhesive firmly adhere to the surface of a Cu-mesh laminate and make air bubbles disappear, in the process (6) shown in Fig. 2, we applied a heating and pressurizing process by utilizing an autoclave after laminating a polymeric film on a Cu-mesh laminate. Pressurizing to 0.5–1.5 MPa makes the acrylic adhesive

adhere to the Cu-mesh surface firmly, and makes air bubbles diffuse into the adhesive and then out. Heating at a temperature of 45–75°C makes the fluidity of the transparent adhesive higher so that above effects of pressurizing might be more effective. By applying a heating and pressurizing process, we obtained a clear Cu-mesh laminate with a low transmission haze of ca. 3%.

4 Applications of organic dyes

For practical use, the transmittance of optical filters in the near-infrared region of 800–1100 nm should be less than 20%, preferably less than 10%.

Sputtered multilayered coatings used for conventional optical filters^{1,2} have a high NIR-blocking ability since its silver layers have a high NIR reflectivity. Indifferent to this, the Cu-mesh laminate has a very low NIR-blocking capability since its opening has neither NIR-reflectivity nor NIR-absorbing power.

Therefore, an optical filter using a Cu-mesh laminate needs to have an NIR-reflecting layer as the above-mentioned multilayer coatings and/or an NIR-absorbing layer such as a resinous layer containing NIR-absorbing organic dye(s) (NIRA dyes). NIRA dyes are preferable because these can be contained in various forms, such as a resinous coating layer, polymeric film, and transparent adhesive.

In order to reduce the NIR transmittance of optical filters using Cu-mesh laminates to the level needed for practical use, we applied a polymeric film with an acrylic coating layer containing NIRA dyes (NIRA film). NIRA dyes (types of phthalocyanine and diiminium) were selected in view of the NIR-absorbing characteristics, durability, *etc.*

Furthermore, since the NIRA film has a greenish and yellowish transmitted color that could deteriorate the picture quality of PDPs, we should adjust the transmitted color of optical filters to a more appropriate one such as neutral gray or bluish gray. In addition, in order to enhance and/or improve the picture quality of PDPs, the visible-light transmission properties of optical filters should be designed from the viewpoint of visible-light transmittance, (bright-room) contrast, surface color which defines the black image of the PDP, color reproducibility, color temperature, minimum perceptible color difference of the white image, *etc.*

To control the visible-light transmission properties of optical filters, we applied organic dyes that have a proper light-absorption band in the visible-light region (380–780 nm) and applicable solubility and durabilities, and we utilized the software tool we had developed to simulate optical designs.^{1,2} In order to apply organic dyes, we chose dye-containing transparent adhesives (DTA) among the various possible forms because it is easy to prepare. Because dyes having a proper light-absorption band for tuning transmission properties, types of anthraquinone, phthalocyanine, azo, pyromethane, porphirin, *etc.*, were chosen and have been applied to the optical filters.

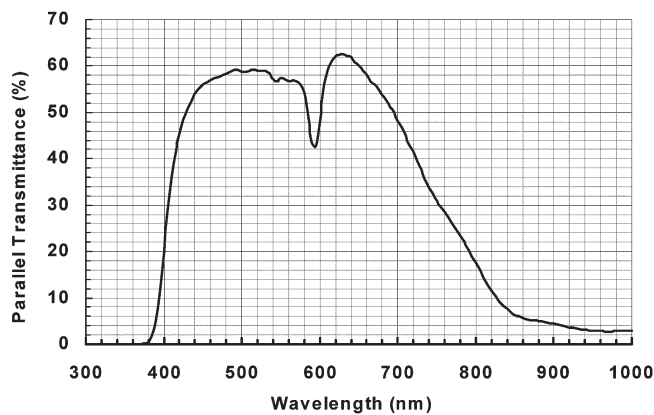


FIGURE 4 — Transmission spectrum of an optical filter using a Cu-mesh layer and the NIRA film. This optical filter with an optically designed dye-containing adhesive has a visible-light transmittance of ca. 59% and a transmitted color (C light source) of $(x, y) = (0.308, 0.321)$.

Figure 4 shows an example of the transmission spectrum of an optical filter using the obtained Cu-mesh laminate, the NIRA film, an anti-reflection film (NOF Corporation: Realook 7702UV), and a DTA of which we designed the transmission properties. This optical filter has a visible-light transmittance⁶ of approximately 59%, a transmittance at 850 nm of ca. 6%, and one at 950 nm of ca. 3%. The sharp absorption band with a peak wavelength of around 595 nm is purposed to reduce the undesirable emissions by a red phosphor (593 nm) and neon gas (585 nm) which lowers the color reproducibility of PDP.²

5 Experiment and results: EM-shielding test

Intensity levels of electric-field radiation of a 42-in. PDP TV with and without optical filters were measured in conformity with the VCCI (Voluntary Control Council for Interference by Information Technology Equipment, Japan) technical criteria (measuring distance, 3 m).

Figure 5 shows the electric-field radiation spectra of [A] the 42-in. PDP TV without an optical filter, [B] the 42-in. PDP TV with a conventional optical filter which has sputtered-multilayer coatings with a surface resistance of $2.4 \Omega/\text{h}$, and [C] the 42-in. PDP TV with an optical filter which has a Cu-mesh layer with a surface resistance of $0.05 \Omega/\text{h}$.

As shown in Fig. 5, we found that the optical filter using the Cu-mesh layer has a much higher EM shielding ability than the conventional optical filter. In the frequency region where [B], the PDP TV with a conventional optical filter, shows a high intensity level of radiation, for example, 30–150 MHz, the radiation intensity level of [C], the PDP set with the optical filter using the Cu-mesh layer, is around 10–20 dB lower than that of [B], the PDP set with the conventional optical filter. The intensity level of [C], the PDP set with an optical filter using the Cu-mesh layer, satisfied the requirement for consumer use (Class B) regulated by VCCI (<40 dB at 30–230 MHz, measuring a distance of 3 m).

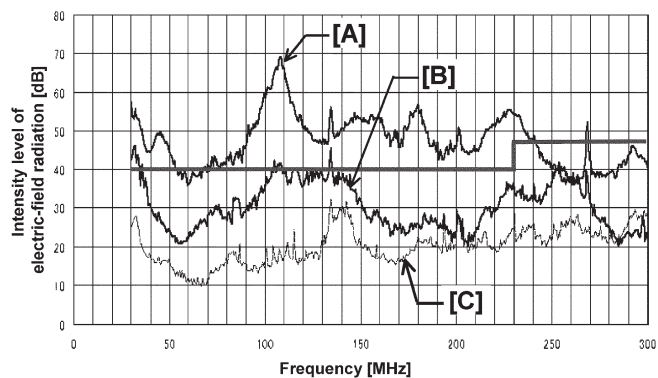


FIGURE 5 — The electric-field radiation spectra of a 42-in. PDP without and with optical filters. The requirement for Class B regulated by VCCI (measuring distance, 3 m): <40 dB at 30–230 MHz, <47 at 230–1000 MHz. [A] the 42-in. PDP set without optical filter. [B] the 42-in. PDP set with a conventional optical filter using sputtered-multilayer coatings with a surface resistance of $2.4 \Omega/\text{h}$. [C] the 42-in. PDP set with an optical filter using the Cu-mesh layer with a surface resistance of $0.05 \Omega/\text{h}$.

6 Summary

The combination of a Cu-mesh layer with a high electrical conductivity and the layers containing organic dyes with appropriate absorbing bands enables us to obtain optical filters for PDPs not only to realize high EM shielding but also to realize NIR reduction and improvement in the PDP's picture quality. We obtained optical filters with a high conductivity by utilizing a Cu-mesh layer, which was processed by a highly productive roll-to-roll photolithography and roll-to-roll etching process. The Cu-mesh layer had a surface resistance of $0.05 \Omega/\text{h}$ and an opening ratio of ca. 93%. Applications of organic dyes and an example of the structure of the optical filter were also presented.

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