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Controlling chromaticity by lamellar gratings

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Abstract. Fundamental numerical study on controlling chromaticity with the simplest diffractive structure is carried out. Observed various characteristics on transmission/reflection and dielectric/metal will be useful guidelines for practical optimisation of device structures.

1 Introduction

There have been many reports on generating wide variety of colours by metasurfaces: originally based on metals and then attempted with dielectrics [1, 2]. Noticing range of colour achieved in reported works is relatively limited, we wish to find factors which influence chromaticity. In order to conduct the task through electromagnetic numerical simulation with Fourier modal method, we employ one-dimentional lamellar gratings, because the simplest structure is suitable to concentrate on the least necessary design freedoms.

2 Method

A considered model is shown in Figure 1: a grating is normally illuminated by a plane wave. As grating materials, we assumed two types of optical glasses, fused silica and SF11, and two types of metals, gold and silver. Glasses are illuminated from a substrate side ($\varepsilon_1 > \varepsilon_2 = 1$) and both reflected and transmitted light are taken into account, whereas metals are illuminated from vacuum side ($\varepsilon_1 = 1$) and only reflection is considered. The light source is CIE standard illuminant D65.

Diffraction efficiencies of zeroth-order plane wave either in reflection or transmission is processed to obtain chromaticity in CIE 1931 colour space. In our present study, the spectrum is limited between 380 and 780 nm.

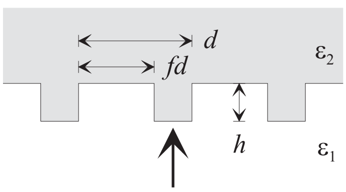

Figure 1. Considered problem.

For the grating structure in Figure 1, there are three design freedoms: period d, depth h and fill factor f. In the present study, we evaluated chromaticity of full combination of $d = 200, 400, \cdots 1800$ nm, $h = 200, 400, \cdots 2000$ nm, and $f = 0.1, 0.2, \cdots 0.9$, in total 810 cases for each grating material. Typical results are shown in Figure 2, where solid and open circles denote all 820 values for gold gratings in reflection and fused silica gratings in transmission, respectively. It is seen that the two materials have noticeably different colour features. Only TE polarisation results are included in this figure. Although TE and TM illumination certainly give different results, only TE results are presented in this report considering our purpose: fundamental study on influencial design freedoms.

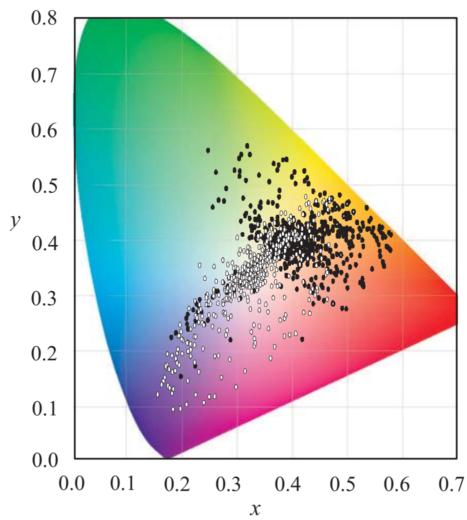

Figure 2. Example chromaticity diagram. •: gold. ○: fused silica in transmission.

All previous study of this topic have stuck to subwavelength structure, because higher-order diffraction is obviously an obstacle when considering practical applications such as colour printing, However, our main motivation here is not finding an optimised grating structure for a particular colour, but investigating influential factors to control chromaticity. Therefore all available design freedoms and their wide combination must be considered.

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In order to handle large number of chromaticity data, directly looking at chromaticity diagram such as Figure 2 is not always convenient. Instead, chromaticity coordinates are converted into relative ones in respect of white point as explained in Figure 3, i.e. from (x, y) to (ρ, ϕ). The white point for D65 is (0.313, 0.329).

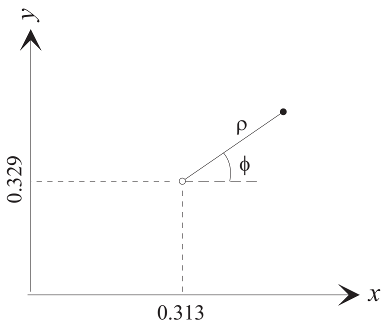

Figure 3. Evaluation of colour diversity. ρ: distance. ϕ; direction. ∘ denotes white point for D65.

3 Results

Relative chromaticity coordinates (ρ, ϕ) defined above are compared among four grating materials: in total six grating modes including reflection/transmission. An example results are shown in Figure 4, where each data point represents maximum value of ρ within 90 combinations of 10 depths × 9 fill factors at each period. This exhibits a degree of saturation, i.e. how far away colour from white can be achieved. Similar graph is obtained for the direction ϕ. This one exhibits a degree of hue, i.e. diversity in colour around the white point. This particular Figure 4 indicates that metal and dielectric gratings in reflection mode show similar tendencies, i.e. maximum distances from the white point are less dependent on periods. On the other hand subwavelength dielectric gratings in transmission-mode perform pretty poorly as colour generators. In more detail, the output light from all 90 structures spanning $200 \leq h \leq 2000$ nm and $0.1 \leq f \leq 0.9$ at $d = 200$ nm present little difference from incident white colour.

We conducted similar observation of ρ and ϕ dependence on depth and fill factor as well. The followings are a list of noticeable findings.

- Subwavelength dielectric gratings in transmission mode do not function as colour generators. This is due to high transmission diffraction efficiencies.
- Range of ϕ is roughly all directions except that ρ of gold grating is limited within fairly narrow range, i.e. well lower than one radian, for $d \leq 600$ nm.
- Dielectric gratings in transmission node need at least 600 nm depth to achieve enough ρ.
- Silver gratings show relatively poor performance in $d \geq 1000$ nm.
- ρ of gold grating is limited within two radian for $d \geq 400$ nm.
- Middle range fill factors, i.e. $0.4 \leq f \leq 0.6$ are preferred in both ρ and ϕ range for all six grating modes.

4 Summary and discussion

Controlling chromaticity with lamellar gratings is investigated in detail n terms of diffractive optics assuming metal and optical glass as grating materials. Some useful information is obtained as presented above, though we have not yet fully analysed the observed data, because the quantity of them is too much to quickly handle.

Many readers may be critical of our inclusion of non-subwavelength gratings. However, gratings in the resonance domain ($d \approx \lambda$) have an attractive feature of rapid change of diffraction efficiency owing to Wood's anomaly. As chromaticity can be regarded as a complicated function of output spectrum, rapid change of efficiency add extra freedom to the spectrum.

In addition to chromaticity, diffraction efficiency is also obtained for each grating structure, though such information is not included here, However, it should be mentioned that high diffraction efficiency over wide spectra is not welcome, but rather disadvantageous. This keeps obtained chromaticity coordinates close to the white point. In this respect, our attempt to employ optical glass gratings in transmission mode may not be a good choice. Instead, non-metal materials with large absorption would be interesting option.

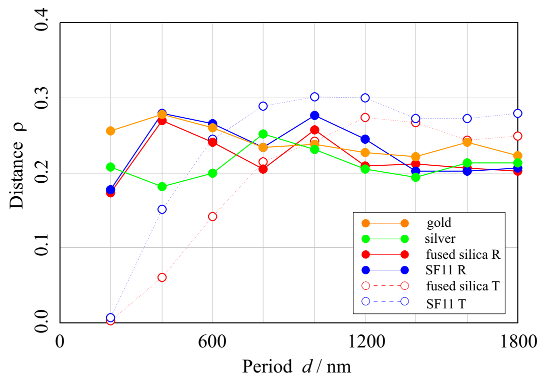

Figure 4. Influence of period on distance ρ. R: reflection. T: transmission.

References

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