X-ray created metamaterials: applications to metal-free structural colors with full chromaticity spectrum and 80 nm spatial resolution.

Marcella Bonifazi¹, Valerio Mazzone¹, Andrea Fratalocchi¹

¹ *PRIMALIGHT, Faculty of Electrical Engineering; Applied Mathematics and Computational Science, King Abdullah University of Science and Technology (KAUST), Thuwal 239955-6900 Saudi Arabia
marcella.bonifazi@kaust.edu.sa*

Abstract: We created new types of metamaterials by hard X-rays possessing high fluency. We discuss applications in structural colors that show full spectrum of Cyan, Yellow, Magenta, Black (CYMK), realized in transparent dielectrics with 80 nm resolution.

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1. Main Text

X-ray interaction with matter is a subject that fascinates scientists since the first x-ray image was captured by chance on a photographic plate in 1895 [1]. Today, the large part of applications of X-rays is still dominated by imaging, ranging from bio-medical diagnostics to the investigation of atomic structures in crystallography [2–6]. The study of how X-rays can change matter, on the contrary, is still at an embryonic stage of development despite its huge potential [7,8].

In this contribution we illustrate how to use hard X-rays with high energy to create new types of nanomaterials, which are based on strong X-ray-matter interactions. We will discuss here the first application of this technology in the field of structural coloration, which is today an intense field of research due to the many possible applications that can be enabled by this technology, such as high resolution micro/nano printing, anti-counterfeiting stamps and biomimetic devices [9–11]. The current state of art in this field of research is dominated by two-dimensional metallic plasmonic metasurfaces, with diffraction limited resolution (140nm) [12]. These structures are based on combinations of noble expensive metals arranged in periodic patterns that are very challenging to scale up and still do not show a complete spectrum of colors.

On the contrary, we will here present experiments showing new X-rays created metamaterials capable of displaying a full spectrum of CYMK colors (including black, red and other colors that are normally created in Nature by pigments and not structures), with a sub diffraction limited resolution as low as 80 nm. These colors are also based on fully random three dimensional nanostructures realized in metal-free cheap materials, and at such are easily scaled up.

Figure 1 shows some experimental results of this technology. To illustrate the capabilities of this technique we printed the letters α and β varying the exposure and design parameters both outside and inside the designs, spanning a wide range of colors, from magenta to black on the left column and from cyan to orange on the right one. It is clear from the SEM images of details provided (Figure 1a, central panels) that the pattern we reproduce follows precisely the profile of the printed image and due to its intrinsic disorder it is not affecting the overall resolution. As a further example of the color and tonal control achieved we printed the word “light” (Figure 1b). The edges of the shapes are neat and sharp and the colors are uniform all over the image.

These features make this technology ideal for real-world applications of structural colors, ranging from nano-imprinting to anti-counterfeiting. Not limited to structural coloration, this approach opens also a complete new way to create nanomaterials with advanced functionalities by exploiting X-Rays and strong light-matter interactions at the Angstrom scale level.

Fig. 1. **a**. Top view images of two letters from the greek alphabet. The sample is nanostructured with two different patterns for the letter and for the background in order to obtain different colors. Results are shown for different doses in the columns on both sides of the panel. SEM details of the sample are shown in the central part of the panel. **b** top image of the word “light” printed in light blue color.

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