Optics Communications 427 (2018) 139–146

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Subwavelength focusing by optical surface transformation

Fei Sun [a,b,c,*], Sailing He [a,b,c,d]

[a] State Key Laboratory of Modern Optical Instrumentations, Centre for Optical and Electromagnetic Research, JORCEP, Zhejiang University, Hangzhou 310058, China
[b] National Engineering Research Center of Optical Instrumentation, Zhejiang University, Hangzhou 310058, PR China
[c] Zhejiang Provincial Key Laboratory for Sensing Technologies, Zhejiang University, Hangzhou 310058, China
[d] Department of Electromagnetic Engineering, School of Electrical Engineering Royal Institute of Technology (KTH), S-100 44 Stockholm, Sweden

ARTICLE INFO

Keywords:
Optical surface transformation
Sub-wavelength focusing
Optic-null medium

ABSTRACT

We propose a novel beam-compression device to achieve sub-wavelength focusing (SF) by optical surface transformation (a new theoretical branch derived from transformation optics). When a Gaussian beam is incident on the input surface of our device, we can obtain a sub-wavelength focused spot at the output surface of the compression device. The focused mode can still propagate to the far-field and keep very good directivity as incident Gaussian beam. The size of the sub-wavelength beam can be tuned by changing the size of the output surface. We only need one kind of homogeneous anisotropic medium, the optic-null medium (ONM), to realize the proposed beam-compression device. After some simplifications, we design a layered structure of two isotropic homogeneous media to realize the device. Numerical simulations verify the performance of our beam-compression device.

1. Introduction

Due to the wave nature of the light, the sizes of the focused beams by conventional lenses are often diffraction limited [1]. Focusing light or electromagnetic waves on the sub-wavelength scale has many important applications, including super-resolution imaging, precision optical processing/manipulation, waveguide couplings, optical data storage, microstructure surface detection, etc. In particular, focusing the light energy on the nano-scale in optical bands has made important revolution changes in many technologies, such as nano manufacture technology [2], nano-optical antennas [3] and nano-imaging [4]. The classical method to achieve a strong focusing is using high numerical apertures [5], which cannot be utilized to achieve a subwavelength focusing (SF) due to the limited value of refractive index. In recent years, there have been many studies on achieving SF by various novel methods, including surface plasmon-polaritons [6–9], Fresnel zone plates [10–12], near-field planes [13,14], super-oscillation lenses [15,16], inhomogeneous media inside some waveguide systems [17,18], special polarized beams [19,20], etc.

Fresnel zone plates, composed of layered opaque and transparent concentric rings can provide compensation for the momentum using the 'grating' structures on the direction vertical to the optical axis to produce evanescent components that are crucial to form a SF [10–12]. Fresnel zone plates have many special features, including elongated depth of focus, no higher order foci, high transmission efficiency, compact device (a thin plate). However, there is no strict theory on how to design Fresnel zone plates to achieve a subwavelength focusing spot with pre-designed dimension (the common method is a large amount of numerical simulations to find the closest size). Near-field plates are based on the interference of evanescent waves in the near field, whose performance is weakly affected by losses [13,14]. A subwavelength spot ($\lambda/18$) in microwave frequency around 1 GHz has been experimentally demonstrated by near field plates [14]. However, the designing process of near-field plates is very complex, which limits its applications. Super-oscillation lenses can achieve a far-field sub-wavelength focused beam (however, with inevitable oscillating side-lopes) without using any evanescent components. In 2015, an enhanced resolution of 35 nm in the visible spectrum was experimentally demonstrated [15]. However, to achieve a smaller subwavelength focused beam, it has to rely on various numerical optimization algorithms. It often lacks a well-developed theory to achieve a smaller sub-wavelength spot of an approximate pre-designed size by super-oscillation lenses.

Surface plasmon-polaritons (SPPs) on metal nano-structures are another way to achieve a sub-wavelength control of light [6–9]. The propagation mode of light in free space is converted to the SPP mode on the metal surface by a tapered metal rod or some other metal structure

* Corresponding author at: State Key Laboratory of Modern Optical Instrumentations, Centre for Optical and Electromagnetic Research, JORCEP, Zhejiang University, Hangzhou 310058, China.
E-mail address: sunfei@zju.edu.cn (F. Sun).

https://doi.org/10.1016/j.optcom.2018.06.029
Received 12 April 2018; Received in revised form 23 May 2018; Accepted 11 June 2018

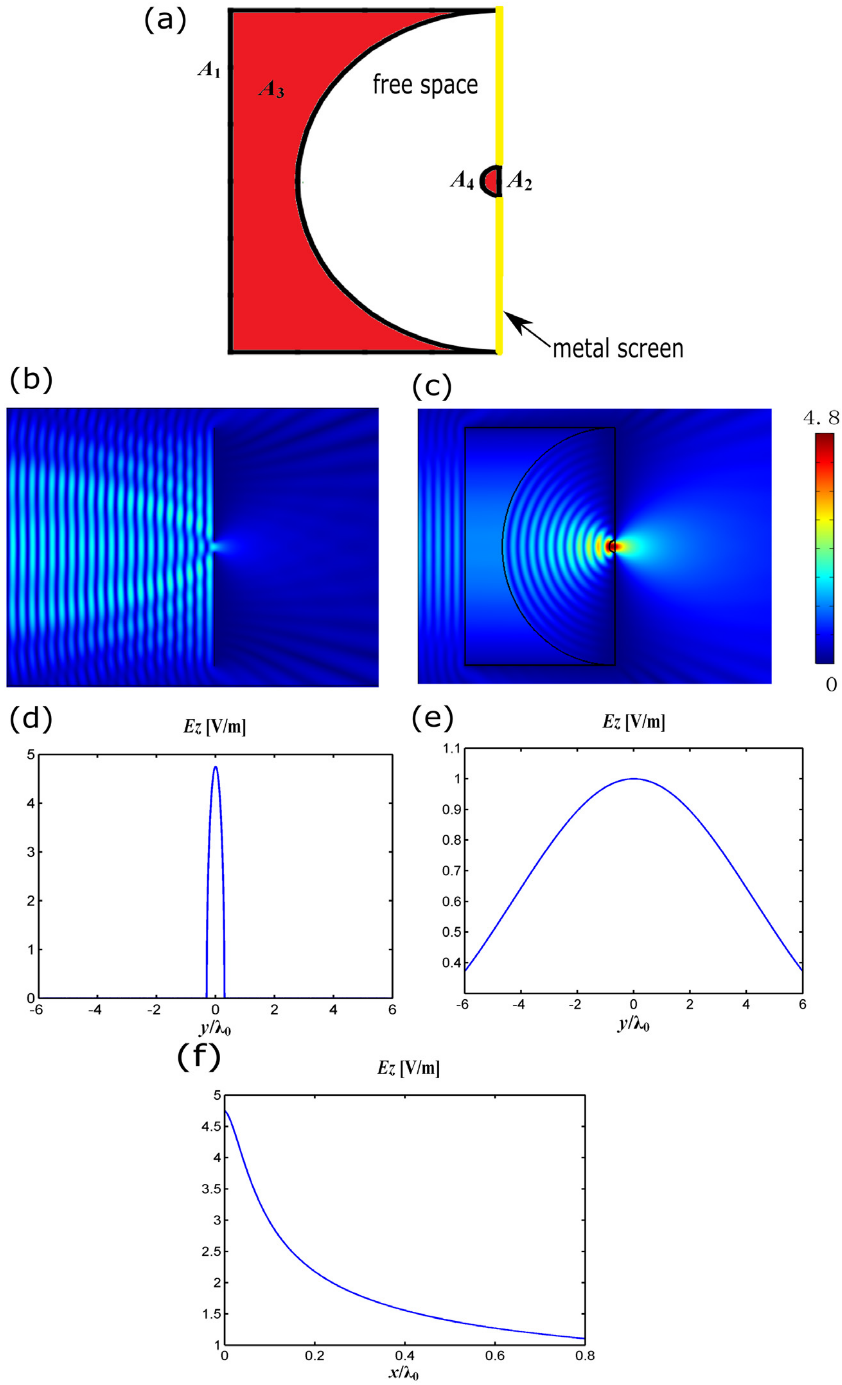

Fig. 1. (a) the basic structure of our beam-compression device: the input plane A_1 and the output plane A_2. The media colored red is ONM with its main axis along the x direction. All other regions (white color) are free space. The yellow lines are perfect electric conductors (i.e. the metal screen). (b) 2D numerical simulation when a Gaussian beam incidents on a metal screen with the subwavelength slit whose radius is $A_2 = 0.12\lambda_0$. We can obtain a beam of the subwavelength size immediately after the screen. However, the efficiency is quite low, as most part of incident wave is blocked, without any focusing (the focused spot can hardly be detected). (c) 2D numerical simulation results for the amplitude of the electric field's z component distribution (TE wave case). The slit on the metal screen with the same size as (b) ($A_2 = 0.12\lambda_0$) is enclosed by our beam-compression device. Here, we choose $A_1/A_2 = 20$ and the amplification factor $A = 8.72$. (d) and (e) are amplitudes of the electric field distribution along the y direction on the output plane A_2 with and without our device, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(also referred as a plasmonic device). As the wavelength of SPPs mode on the metal surface is much smaller than the wavelength of the light in free space, the localized focused beam is on the sub-wavelength size (i.e. nanometers for visible light). SPPs provide a simple way to achieve a sub-wavelength spot, which has resulted in the development of many nano-optical applications, e.g. optical trapping, nano-photonic circuits, etc. At first, it still lacks theoretical models to design these plasmonic devices, and people must study various plasmonic devices by numerical simulations and experimental measurements [9]. As a powerful theoretical tool, transformation optics (TO) [21–26] has progressed and become an important and effective theoretical method to design novel optical devices that can modulate the propagation of light [27–31], polarization [32,33], wave-front [34], and field distribution [35,36]. In recent years, TO has been extended to design plasmonic devices