Optics Communications 382 (2017) 477–484

Contents lists available at ScienceDirect

Optics Communications

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

An analysis of the surface-normal coupling efficiency of a metal grating coupler embedded in a Scotch tape optical waveguide

Carlos Angulo Barrios [a,b,*], Víctor Canalejas-Tejero [a]

[a] Instituto de Sistemas Optoelectrónicos y Microtecnología (ISOM), ETSI Telecomunicación, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain
[b] Department of Photonics and Bioengineering, ETSI Telecomunicación, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 1 July 2016
Received in revised form
3 August 2016
Accepted 15 August 2016

Keywords:
Micro-optical devices
Diffraction gratings
Subwavelength structures
Guided waves
Polymer waveguides
Integrated optics devices

ABSTRACT

The coupling efficiency at normal incidence of recently demonstrated aluminum grating couplers integrated in flexible Scotch tape waveguides has been analyzed theoretically and experimentally. Finite difference time domain (FDTD) and rigorously coupled wave analysis (RCWA) methods have been used to optimize the dimensions (duty cycle and metal thickness) of Scotch tape-embedded 1D Al gratings for maximum coupling at 635 nm wavelength. Good dimension and tape refractive index tolerances are predicted. FDTD simulations reveal the incident beam width and impinging position (alignment) values that avoid rediffraction and thus maximize the coupling efficiency. A 1D Al diffraction grating integrated into a Scotch tape optical waveguide has been fabricated and characterized. The fabrication process, based on pattern transfer, has been optimized to allow complete Al grating transfer onto the Scotch tape waveguide. A maximum coupling efficiency of 20% for TM-polarized normal incidence has been measured, which is in good agreement with the theoretical predictions. The measured coupling efficiency is further increased up to 28% for TM polarization under oblique incidence. Temperature dependence measurements have been also achieved and related to the simulations results and fabrication procedure.

1. Introduction

Implementation of photonic and optoelectronic devices and systems on flexible supports is a subject of increasing interest because it opens the door to new device functionalities as compared to conventional schemes on rigid substrates. For example, flexible films can be wrapped around curved and angled surfaces enabling conformal integration of photonic sensors and electronics on hemispherical lenses [1] and human body parts [2]. These technologies can also produce tunable optical devices for adaptive photonic systems [3] and flexible waveguides for interconnections [4–6]. This has boosted research and development of innovative optical materials and nanofabrication methods targeting simplicity, low cost, high-throughput and mass production.

Polymeric materials have been traditionally used to implement flexible optical configurations as they can be customly synthesized to offer targeted optical, mechanical and thermal characteristics. This can be done by properly engineering the chemical composition, doping (e.g. with dyes or nanoparticles) and synthesis conditions of the polymers. In addition, inorganic materials, like chalcogenide glass [7] and Si [8], can be incorporated by well-known techniques such as low-temperature deposition and pattern transfer onto polymeric substrates to provide specific optical functionalities (e.g. high-index-contrast and non-linear features).

Conventional pressure-sensitive adhesive (PSA) polymeric tapes, such as Scotch office tapes, are flexible, can be adhered to a variety of surfaces by applying slight pressure without the need for solvent, heat, UV or water for activation. They can also be made highly transparent at optical wavelengths, like general purpose office tapes made of polypropylene films. These characteristics make PSA polymeric tapes suitable material platforms to develop cost-effective and easy-to-use flexible and sticky optical waveguides. To couple light into a PSA tape, out-of-plane (normal) optical coupling appears to be an appropriate procedure due to the quasi-2D geometry of tapes and the difficulty in achieving polished facets for direct in-plane optical coupling. In this respect, diffraction gratings are well-suited configurations [9], particularly when relatively large spot beams are to be coupled, a planar coupling structure is required, and the application is not critically power limited.

In a recent work [10], we reported the first demonstration to our knowledge of an easy-to-fabricate flexible optical waveguide interconnecting device made of a PSA Scotch tape with integrated

---

[*] Corresponding author at: Instituto de Sistemas Optoelectrónicos y Microtecnología (ISOM), ETSI Telecomunicación, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain.
E-mail address: carlos.angulo.barrios@upm.es (C.A. Barrios).

http://dx.doi.org/10.1016/j.optcom.2016.08.037
0030-4018/

Al diffractive grating couplers. The latter consisted of 2D nanohole arrays (NHAs) drilled in an Al thin film incorporated to the PSA tape by using a simple stick-and-peel transfer procedure [11]. Due to the NHA 2D geometry (square lattice), light incident onto the grating coupler was split into four normal propagation directions in the tape waveguide, resulting in a low one-direction coupling efficiency (3.6%). For most applications, maximum coupling into a given direction is desirable, for which a 1D (stripe array) grating coupler is advantageous over a 2D configuration. In this work we address this issue by analyzing the surface-normal coupling efficiency of a 1D Al grating coupler embedded in a Scotch tape waveguide. The analysis is focused on normal incidence in order to evaluate the capability of the coupler to be directly adhered onto the flat active surface of semiconductor light sources (light emitting and laser diodes) and photodetectors. The coupling grating is modeled through computer simulations to determine the optimal dimensions (duty cycle, metal thickness and grating length), sensitivity to the tape refractive index, and best incident beam parameters that maximize the surface-normal coupling efficiency. Based on the theoretical analysis, an actual device that increases significantly the aforementioned reported one-directional coupling efficiency is demonstrated, and both, its temperature dependence and angular response are measured.

2. Device fabrication

2.1. Aluminum 1D grating fabrication

Al 1D gratings were first fabricated on a 1 cm × 1 cm polycarbonate (PC) substrate from a standard compact disc (MPO Iberica, Madrid, Spain) as follows [12]. The PC chip was washed with detergent in ultrasonic bath, rinsed in deionized water (DIW) and isopropyl alcohol and dried with N_2 flow. Then, an e-beam evaporated 100-nm-thick layer of Al was deposited on the flat surface (i.e., with no track) of the PC substrate. Next, ZEP-520 positive tone e-beam lithography (EBL) resist was spin-coated on the Al surface resulting in a 120 nm thick resist film. The chip was then immediately baked for 10 min at 120 °C to remove solvent residues and improve both resist uniformity and resist adhesion to the substrate. Stripe arrays of 500 nm pitch were patterned in the resist film by using a Crestec CABL-9000C high resolution EBL system (acceleration voltage = 50 keV, beam current = 100 pA, exposure time = 100 μs). The exposed resist was developed at −15 °C for 10 s and N_2-dried. Next, inductively coupled plasma (ICP) chemical dry etching was used to drill lines in the Al layer down to the PC substrate using the patterned ZEP-520 film as a mask. The ICP process was achieved using BCl_3 (20 sccm) and Cl_2 (10 sccm) gases, and RF and ICP powers of 100 W. Immediately after the ICP etch, the chip was rinsed in DIW for 5 min to dissolve residual $AlCl_3$. Then, O_2 plasma was used to remove resist residues. Finally, the chip was exposed to an additional O_2 plasma treatment to allow subsequent nanostructured Al film delamination.

The latter plasma step was a necessary modification relative to our previous fabrication of releasable NHAs on PC [10,11]. The EBL writing time for defining stripes was much longer than that for nanoholes. This over-exposure modified the PC surface, increasing the Al stripe-PC bonding strength and avoiding the complete subsequent detachment of the 1D Al gratings by a stick-and-peel procedure. The plasma oxygen treatment solved this problem by slightly etching PC and critically undercutting the Al stripes. The undercut decreases the interfacial area between Al and PC, weakening the bonding force between them. Fig. 1(a) and (b) shows a photograph of two 1.2 mm × 1.2 mm Al 1D gratings fabricated on PC and a scanning electron microscope (SEM) top grating image (stripe width ~270 nm), respectively.

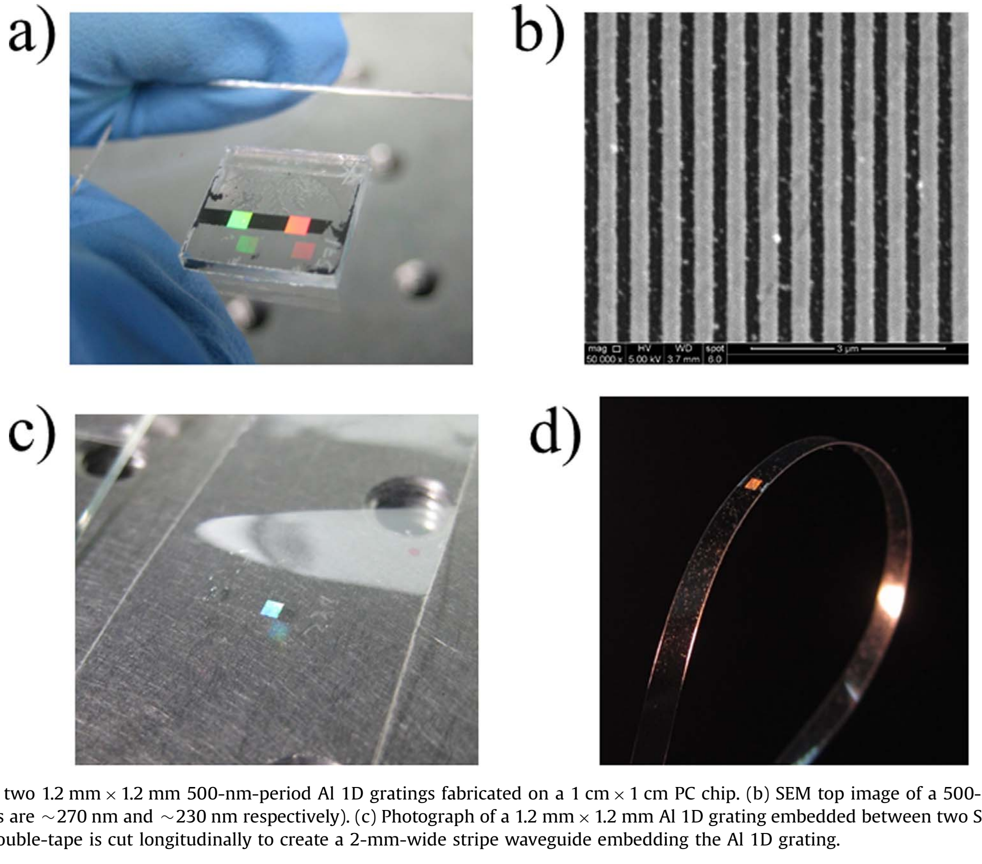

Fig. 1. (a) Photograph of two 1.2 mm × 1.2 mm 500-nm-period Al 1D gratings fabricated on a 1 cm × 1 cm PC chip. (b) SEM top image of a 500-nm-period 1D Al grating (stripe and groove widths are ~270 nm and ~230 nm respectively). (c) Photograph of a 1.2 mm × 1.2 mm Al 1D grating embedded between two Scotch tapes (double-tape configuration). (d) The double-tape is cut longitudinally to create a 2-mm-wide stripe waveguide embedding the Al 1D grating.