Design of a subwavelength bent C-aperture waveguide

Paul Hansen,[1,*] Lambertus Hesselink,[2] and Brian Leen[1]

[1]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[2]*Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA*
**Corresponding author: pch@stanford.edu*

Received February 7, 2007; revised April 2, 2007; accepted April 9, 2007;
posted April 17, 2007 (Doc. ID 79719); published June 7, 2007

We present a design for a subwavelength C-shaped optical waveguide with a 90° junction that efficiently transports light while maintaining tight confinement with an exit spot size of $\lambda/7$. Finite-difference time-domain simulations of perfect electric conductors and Au C-aperture waveguides are performed for optical frequencies. A design resonant near 780 nm is presented, with a spot size of $107\ \text{nm} \times 107\ \text{nm}$ and an energy density enhancement factor of 10 for a bent waveguide of total length 1.4 μm. © 2007 Optical Society of America

OCIS codes: 050.1220, 130.2790, 130.0250, 230.7370.

Today's research push toward small, fast photonic circuits depends on the creation of small integrated optical interconnects. Such components must support tightly confined modes of light with low attenuation. Power delivery components for heat-assisted magnetic recording (HAMR) systems must also deliver high-intensity light with subwavelength confinement. Because it may not be possible to introduce the light beam in the desired direction in a HAMR system (i.e., normal to the recording surface), the capability to guide light through a tight corner with low losses is essential. This Letter presents a design for an optical frequency C-aperture waveguide with a 90° bend, which is ideal for these and other applications. We show that the energy density enhancement and small spot size of the resonant C aperture remain and that efficient propagation through the corner of the guide is possible, with transmission comparable with that of the straight waveguide.

We have previously reported the design of a resonant C-aperture waveguide, operating at optical wavelengths, which exhibits high throughput, tight confinement, and enhanced energy density at the exit port with low heat and radiative losses [1]. The effects of evanescent decay are mitigated by surface plasmon resonances in the waveguide walls. Plasmon effects are one of a host of techniques under investigation for enhancing transmission through subwavelength apertures. Using grooved facing surfaces [2], filling apertures with high-index medium [3,4], and exploiting Fabry–Perot thickness resonances in thin slits [5] all have been shown to reduce loss and increase transmission. Open subwavelength V-groove structures have been used to make low-loss micrometer-size resonators and interferometers [6]. Like the thin-film C aperture, this waveguide exploits surface plasmon effects to enhance energy density on transmission—the peak energy density measured close to the exit of the waveguide is up to 40 times higher than the peak energy density of the plane wave incident on the entrance [7]. The waveguide is thus suitable for high-intensity power delivery. The C-aperture waveguide utilizes the same propagation mode as conventional metal ridge waveguides, featuring a much longer cutoff wavelength than rectangular waveguides of the same area. Such waveguides confine propagating modes to a transverse area of approximately $\lambda/5 \times \lambda/5$. At optical frequencies, the skin depth of the waveguide material (gold in the present simulations) alters the effective waveguide shape, and the conductivity leads to ohmic losses in the sidewalls. Fortunately the long-wavelength fundamental guide resonance mitigates against conductive losses.

The C-aperture waveguide is derived from the thin-film C aperture by increasing the thickness of the metal film to several times the skin depth for the design wavelength. The C aperture is particularly notable for its high throughput at resonance and very small spot size [8]. Power flow analysis of the C aperture at resonance indicates that its effective cross section—the area from which it gathers light—is far larger than its actual cross section [9]. Transmitted light concentrates near the tip of the ridge with an energy density that is far higher than in the incident plane wave. C-aperture waveguides also exhibit field enhancement.

The C-aperture waveguide inherits its dominant propagation mode from ridge waveguides. The properties of the ridge waveguide are familiar to microwave researchers. Insertion of a ridge into the side of a rectangular waveguide increases the cutoff wavelength for the guide. The cutoff wavelength of the ridge waveguide greatly exceeds its cross-sectional dimensions and causes the tight confinement we see in the C-aperture waveguide. (A resonant square waveguide with the same confinement must operate at a much shorter wavelength and will not exhibit the C-aperture collection property.)

We used the finite-difference time-domain (FDTD) method to simulate transmission through bent C-aperture waveguides with equal-length input and output arms. For comparison purposes, we also simulated straight waveguides with the same cross sections as the bent waveguides. In the first set of simulations, the waveguides were made of perfect electric

 © 2007 Optical Society of America

conductors (PEC), a fictional opaque and lossless material, to separate attenuation due to evanescent modes from conductive attenuation. In the second set of simulations, we used gold instead of PEC and retuned the waveguide to the same resonant wavelength. The cross section and simulation schematic are in Fig. 1. We have studied several C-aperture designs [10] and here use a ridge shape, which gives rise to a spot with a uniform transverse width. Gold's optical skin depth of ~30 nm softens the waveguide boundary conditions and changes the effective shape of the guide. In a 200 nm wide gold waveguide, the skin depth can increase the modal wavelength by 30%. Penetration into the ridge reduces its effective size and erodes the performance as well. The gold waveguide thus has a substantially smaller cross section than the PEC waveguide resonant at the same wavelength.

In all simulations, a broadband plane wave is incident on the waveguide entrance. The waveguide is embedded in a slab of PEC or gold and filled with free space ($n=1$). The gold is simulated using the Drude model with parameters $\epsilon_\infty=12.9898$, $\omega_p=4.0217\times10^{15}\,\mathrm{s}^{-1}$, and $\tau_c=9.0441\times10^{-15}\,\mathrm{s}$, obtained by a least-squares fit to the tabulated permittivity values from 600 to 1300 nm. We measure the electric fields at the tip of the ridge approximately 20 nm distant from the exit plane of the aperture and compare this value to the field intensity of the incident pulse. A fast Fourier transform (FFT) of the incident and transmitted fields gives the transfer function for the waveguide; the squared modulus of the transfer function yields the energy density enhancement per frequency, which we call the enhancement factor. Additionally, we record the electric and magnetic fields in the transverse plane 20 nm from the aperture exit to calculate the spot size for each frequency of interest. The spot size is defined as the FWHM of the squared electric field amplitude. For heat delivery applications, the near-field electric field energy density and spot size are the most pertinent metrics.

The straight PEC C-aperture waveguide has a strong aperture resonance that begins at 850 nm in the thin-film limit and asymptotically approaches 780 nm as the waveguide grows longer (Fig. 2). This is the dominant mode of the ridge waveguide. With increasing length, the thickness resonances become apparent, spaced roughly one half wavelength apart. The enhancement factor peaks at 55 for very short waveguides but remains above 35 as the waveguide reaches 1.7 μm and beyond; the spot size is 144 nm $\times$ 139 nm.

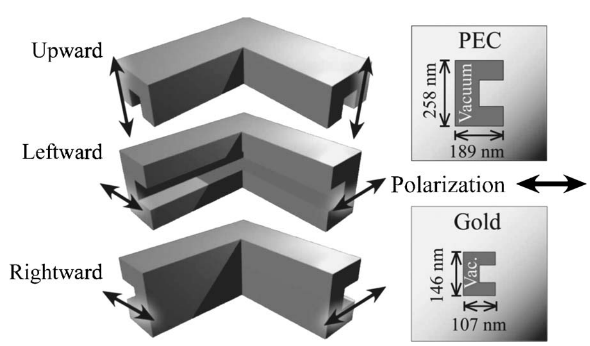

Fig. 1. Waveguide simulation schematic showing the possible orientations for a 90° bend in a C-aperture waveguide, as well as the cross-sectional dimensions of the simulated structures.

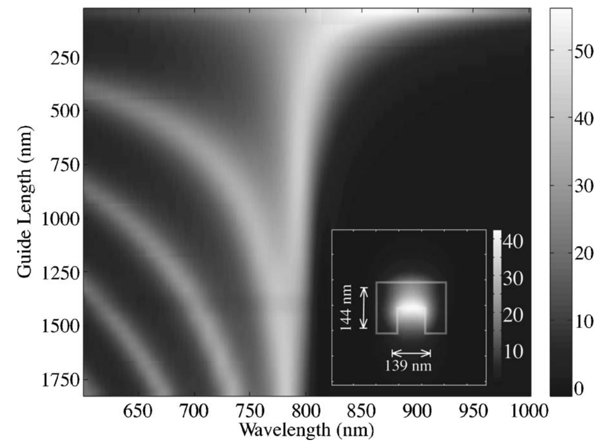

Fig. 2. Enhancement factor, straight PEC waveguide; spot intensity and FWHM (inset). Measurement was taken three cells (25.8 nm) from the exit. Spot size was measured for a 1800 nm waveguide.

There are three ways to turn the waveguide at a junction while keeping the geometry axis aligned. The leftward junction maintains continuity of the ridge around the inside of the turn. The rightward junction is opposite, with the ridge following the outside of the turn. The upward bend (symmetrically equivalent to a downward bend) keeps the ridge in the center of the waveguide in the junction. For each bend type, we fixed the cross section and varied the total waveguide length, constraining the arms of the guide to be the same length. This constraint simplifies the transmission spectrum by making sure that length resonances for the input and output arms coincide. The first experiments compared straight and bent PEC waveguides. After studying these results, we simulated the waveguides again using gold. Field penetration into the gold changes the effective cross section, reducing the transmission efficiency and redshifting the resonances to beyond 1 μm. To compensate, we reduced the cross-sectional area. This reduced the resonance wavelengths and effective aperture size (outline and penetration depth) (Fig. 1), lowering the dominant mode to near the design wavelength of 780 nm.

Comparing the enhancement spectrum of the upward bend with that of the straight waveguide, one notes that the thickness resonances entering on the left have split into pairs. Every resonance corresponds to a length scale in the waveguide structure. The C-aperture resonance, which becomes the ridge resonance in these waveguides, varies with the waveguide's perimeter, as it is due to charge oscillations between the ridge and the spine. The thickness resonances are due to reflections from structural boundaries, such as the ends of the waveguide. The entrance and exit reflections cause the thickness resonances of the straight waveguide. Bent waveguides exhibit these thickness resonances as well as resonances from reflections off the junction.

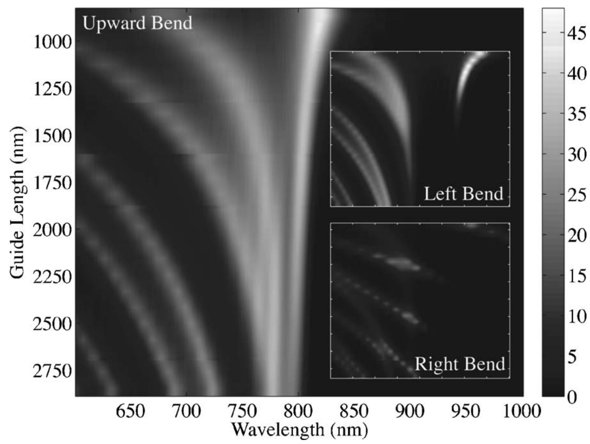

Fig. 3. Enhancement factor, bent PEC Waveguide: upward, rightward and leftward (inset, same intensity scale). Measurement was taken three cells (25.8 nm) from the exit.

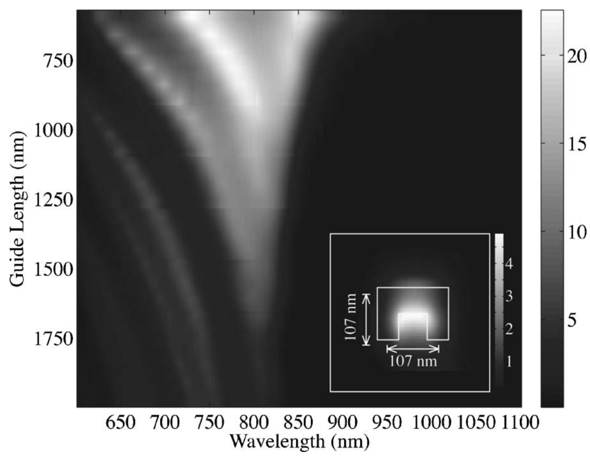

Fig. 4. Enhancement factor, upward bent gold waveguide; spot intensity and FWHM (inset). Measurement was taken three cells (17.85 nm) from the exit. Spot size was measured for a 2140 nm waveguide.

The distance from the waveguide's end to the junction is not quite half the total waveguide length, so the junction reflection resonances do not coincide with the full length resonances. This accounts for the apparent split resonances in the bent waveguide figures. The ridge resonance in the center does not split as it is due to the waveguide perimeter.

All three bent waveguide types (left, right, and upward bends) feature split length resonances. However, the upward bend alone preserves the strong ridge resonance (Fig. 3). Coupling into the ridge mode is strongly polarization dependent, which is known from C-aperture studies [8]. The preferred polarization directions are shown in Fig. 1. The left and right bends both require guided modes to rotate polarization by 90° at the junction, and without a mechanism for this rotation, the ridge mode is severely attenuated (left bend) or absent (right bend). The upward bend retains a strong ridge resonance and comparable enhancement factor to the straight waveguide, so we focus on this case for the remainder of the study.

We simulated upward bent gold waveguides with a variety of half-lengths as in the PEC case (Fig. 4). Despite ohmic losses, the enhancement factor for the upward bend case remains above 10 for a guide of total length 1400 nm, with a spot size of 107×107 nm. The spot size predominantly depends on the size of the waveguide ridge, so the smaller ridge of the gold waveguide produces a correspondingly smaller spot than the PEC waveguide does.

In conclusion, simulations have shown that the C-aperture waveguide with a 90° bend promises a high energy density enhancement and a small spot size for power delivery, while allowing the flexibility to direct the power in any direction. Results for the three possible directions of bend show that an upward bend results in the greatest power transmission, comparable with that of a straight waveguide. These properties make the straight subwavelength C-aperture waveguide suitable for a broad range of integrated power delivery and optical interconnect applications.

We gratefully acknowledge support from Samsung Electronics.

References

1. L. Sun and L. Hesselink, Opt. Lett. **31**, 3606 (2006).
2. J. Seidel, F. I. Baida, L. Bischoff, B. Guizal, S. Grafstrom, D. Van Labeke, and L. M. Eng, Phys. Rev. B **69**, 121405 (2004).
3. F. J. Garcia de Abajo, J. J. Saenz, I. Campillo, and J. S. Dolado, Opt. Express **7**, 7 (2006).
4. F. J. Garcia-Vidal, S. Moreno, J. A. Porto, and L. Martin-Moreno, Phys. Rev. Lett. **95**, 103901 (2005).
5. Y. Takakura, Phys. Rev. Lett. **86**, 5601 (2001).
6. S. Bozhevolnyi, V. S. Volkov, E. Devaux, J-Y. Laluet, and T. W. Ebbesen, Nature Lett. **440**, 508 (2006).
7. X. Shi and L. Hesselink, J. Appl. Phys. **41**, 1632 (2002).
8. X. Shi, R. Thornton, and L. Hesselink, Opt. Lett. **28**, 1320 (2003).
9. L. Sun, R. Batra, X. Shi, and L. Hesselink, in Proceedings of IEEE Visualization (IEEE, 2004), p. 337.
10. X. Shi and L. Hesselink, J. Opt. Soc. Am. B **21**, 1305 (2004).