Conical reflection of light during free-space coupling into a symmetrical metal-cladding waveguide

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Novel conical reflection of light by a thick three-layered metal-clad optical waveguide is observed. A symmetrical metal-cladding optical waveguide is used, which exhibits extraordinary conical reflection during free-space coupling of light to the waveguide. The phenomenon is attributed to the leakage of excited ultrahigh-order guided modes and their inter- and intramode coupling interaction. © 2013 Optical Society of America

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1. INTRODUCTION

The concept of ultrahigh-order guided modes with mode order as high as 10^2–10^3 supported by symmetrical metal-cladding optical waveguides (SMCOW) with an extended thick guiding layer has already been well established and their theoretical model systematically investigated [1]. Ultrahigh-order guided modes possess many fascinating characterstics, such as a small propagation constant, strong negative dispersion, and large Goos–Hänchen shift. The existence of such high-order modes in SMCOW has made them a favorable device in optical sensing and detection. Recently, widespread analysis of the characteristics and potential applications of ultrahigh-order guided modes has been carried out in various experiments, where the guiding layer is typically extended to submillimeter scale. Their novel features are exploited for slow light devices [2,3], superprism spectrometers [4], sensors [5], and precise displacement detection [6–8].

The excitation of ultrahigh-order guided modes in SMCOW is quite different from the conventional method. Routinely, the coupling of light into a waveguide is achieved by the use of prism or grating couplers. Guided modes are excited when the phase matching condition is reached. In a uniform planar waveguide, the propagation constant vector or the propagation direction of the excited mode is parallel to the longitudinal component of the incident light; that is, the guided mode is always excited in a well-defined direction. However, in SMCOW, mode excitation is possible through direct free-space coupling, since the effective index of ultrahigh-order guided modes can be smaller than that of air [1,9].

In this paper, we report on the observation of excited omnidirectional ultrahigh-order guided modes in a uniform three-layer planar SMCOW, which manifest themselves by the occurrence of multiple discrete conical reflections of light. The behavior of the conical rings is dramatically different from those in Newton's rings or Fabry–Perot resonance experiments. The mechanism is explained by a proposed model based on the strong coupling between ultrahigh-order guided modes.

2. THEORY AND EXPERIMENT

For an optical waveguide consisting of a thick guiding layer and double metal-cladding layers, the reduced dispersion equation for the ultrahigh-order guided modes can be written as [1]

$$k_0 h\sqrt{n^2 - N^2} = m\pi, \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wavenumber in vacuum, and h and n are the thickness and the refractive index of the guiding layer, respectively. $N = \beta/k_0$ is the effective index where β is the propagation constant, and m is the mode order. The optical field in SMCOW is confined by normal reflection at the metal-dielectric interface. The result is that the effective index can be smaller than that in free space [9]. For a 100 μm thick SMCOW, in which the mode order is typically of the order of magnitude of 10^2–10^3, the phase shift at the interface is always insignificant and hence neglected here. For ultrahigh-order guided modes, it is only meaningful to explore their characteristics when the effective index is small (near zero) because of the desirable small propagation constant and its extreme sensitiveness to the refractive index and thickness of the guiding layer.

In our experiment, a 90 μm thick of glass slab was sandwiched by two layers of Ag film (34 nm upper layer and 200 nm substrate) deposited in vacuum using the sputtering method. Thinner samples would cause difficulty in the fabrication and also reduce the mode density, while thicker ones would cause the lower-order modes to be inseparable (that is, they would degenerate to free-space propagation rather than stay confined in the waveguide). These three layers construct the simplest form of SMCOW, with the upper thin cladding layer acting as a coupling layer. The structure resembles a Gires–Tournois interferometer (GTI) mirror or a reflected

Fabry–Perot resonator. A SMCOW is also similar to a conventional waveguide but with an "extremely" thick guiding layer. Light is directly coupled into the SMCOW without a prism coupler by means of the free-space coupling method. It is straightforward to have the propagation constant of the excited modes to be $\beta = n_0 \sin \theta$, where $n_0 = 1$ is the refractive index of air and θ is the incident critical angle. Compared with their wave vectors, the propagation constants are small in near-normal incidence scenarios, which reveals the weak directionality character of ultrahigh-order guided modes. The excited modes can easily be scattered to various directions by the imperfection in the guiding layers, such as Rayleigh scattering. Due to the thin upper-layer cladding, leakage of the guided mode power cannot be neglected. The interesting result is that besides the normal reflection of light, there is also a conical reflection phenomenon at the critical angles, as illustrated in Fig. 1.

Our experimental setup is depicted in Fig. 2(a). A beam from a He–Ne laser at the wavelength of 632.8 nm was slightly focused by a long focal length lens ($f = 17.5$ cm) reflected by the SMCOW placed at the focus and then projected on a screen. There was a hole in the screen to let through the incident light. The SMCOW sample was held on a rotation stage to tune the incident angle. The pattern on the screen was recorded by use of a camera.

Away from critical angles, the incident light experienced normal reflection, as shown in Fig. 2(b). The left spot is the hole in the screen for laser incidence. The right blur spot is the reflection light projected on the screen because of scattering due to the imperfection of either the metal-cladding layer or the glass slab. This is also the case of a GTI mirror, in which the reflected light undergoes a phase shift relating to its frequency, the thickness of the SMCOW, and the incident angle. This kind of frequency-dependent phase shift has found usefulness in pulse compression of ultrafast pulses [10]. When the incident angle satisfied the mode coupling condition, the extraordinary reflection emerged as a concentric-ring pattern projected on the screen, as shown in Fig. 2(c). By continually tuning the rotation stage from a normal to small oblique angle of incidence, it alternated between the two patterns shown in Figs. 2(b) and 2(c). In the coupling situations, the pattern of concentric rings remained unchanged with the center always shifting to the middle point; that is, the cone of the reflection was always perpendicular to the waveguide surface. The bright ring pattern appeared when the reflected light spot hit one of the concentric rings. In addition, the intensity of each ring was measured to be equal in all directions, with outer rings having a slightly lower intensity. It should be mentioned that no microstructure was preintroduced in the guided layer or on the cladding layer. The mechanism was not the interference of light reflected by the upper and lower cladding layer either, thus distinguishing itself from Newton's rings or multiple-beam interference as in Fabry–Perot resonance.

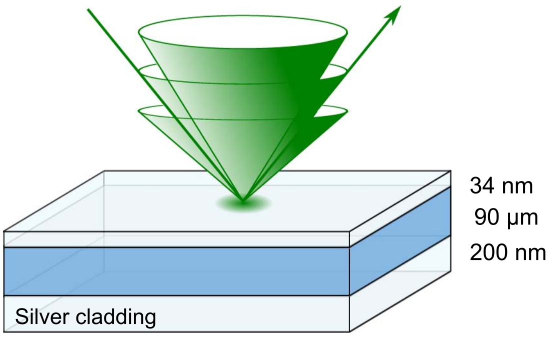

Fig. 1. Light reflected by a SMCOW exhibits extraordinary conical reflection at critical angles, which is the outleakage of omnidirectional guided modes.

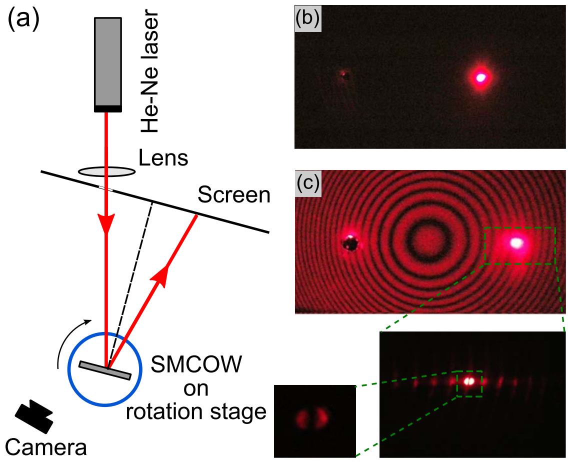

Fig. 2. Experimental setup for the observation of extraordinary conical reflection by SMCOW. (a) Top view of the setup. (b) Normal reflection away from the mode coupling condition. (c) The observed extraordinary conical reflection pattern.

The fact that the generated concentric rings are attributed to the leakage of the excited omnidirectional ultrahigh-order guided modes can be directly affirmed by the appearance of the m line shown in the enlarged insets of Fig. 2(c). The dark line in the reflected light spot shows efficient incoupling of light and the excitation of guided modes. By comparing their half-apex angles with those corresponding critical angles in the attenuated total reflection (ATR) spectrum, one can determine that the formation of the multiple reflection cones is the direct outcoupling of excited adjacent guided modes in SMCOW. As can be seen, although the phase matching constraint determines one efficient well-defined coupling direction, it seems there is no such limitation for ultrahigh-order guided modes.

The angular intensity distribution of the conical reflection is plotted in Fig. 3(a), which intuitively presents the half-apex angles of each reflection conical cone. Figure 3(b) presents the measured and simulated ATR results, which monitor the reflected light intensity versus angles of incidence. Each resonant dip in the curve corresponds to the critical angle and the excitation of one order of ultrahigh-order guide modes. The order of the excited mode can be estimated according to Eq. (1), although the exact value is difficult to determine [12]. Experimental data of the ATR curve at incident angle smaller than 2° are not measured due to practical constraints. By measuring the ATR spectrum, the accurate critical angles are compared with those of half the aperture of the reflection cone, which matches exactly and in good agreement with the theoretical prediction. Thus, it can be reaffirmed that the formation of the ring pattern is the result of the leakage of excited omnidirectional ultrahigh-order guided modes. The simulation gives two different ATR curves by 1 μm increment in the guiding layer thickness, which

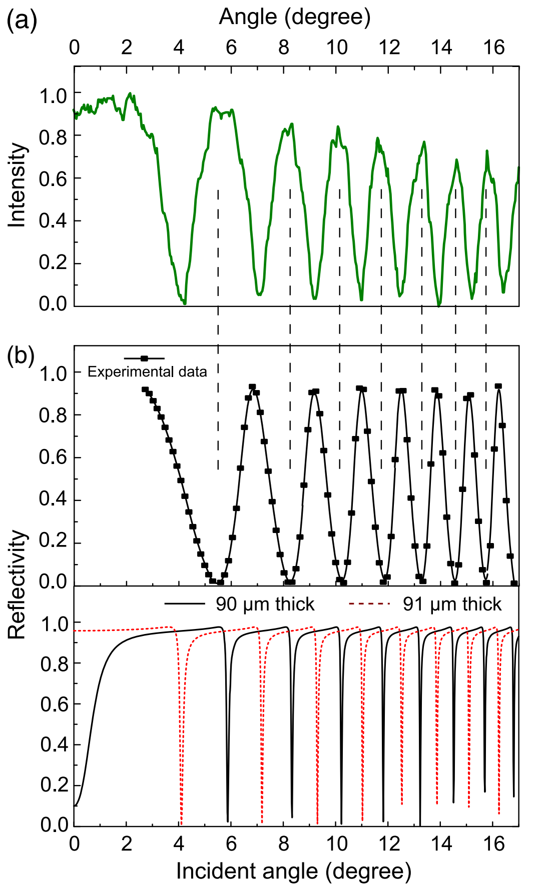

Fig. 3. (a) Normalized angular intensity distribution of the conical reflection. (b) The experimental and simulation ATR spectrum of the SMCOW sample ($\epsilon_{\mathrm{Ag}} = -15.8 + 1.06i$ at 632.8 nm [11]).

shows sensitivity of ultrahigh-order guided modes related to the SMCOW thickness. Whether the center of the conical reflection rings is bright or dark is sensitively related to the thickness of SMCOW, as was seen in our experiment. By slightly translating the SMCOW, the reflection pattern would become complementary to the original one at some point, and the center of the concentric rings would turn dark due to the slightest variation of the thickness of the slab. This is also the basis of precision displacement sensing [6–8].

3. DISCUSSION

To explain the omnidirectional excitation and multiple conical reflection phenomena, here we contribute the excitation of multiple omnidirectional guided modes to the strong inter- and intramode coupling in the waveguide based on scattering perturbation.

We make a comparison between a conventional micron-scale dielectric waveguide and SMCOW, as shown in Fig. 4. From the perturbation theory [13,14], the coupling coefficient between two modes by periodic perturbation can be rewritten in the form of

$$\kappa_c = \frac{\kappa^2}{\beta^2 \Lambda \omega_{\mathrm{eff}}} \left| \int f(x) e^{i2\Delta\beta x} \mathrm{d}x \right|, \tag{2}$$

where κ is the transverse component of the wave vector, Λ is the perturbation period, ω_{eff} is the effective thickness, $f(x)$ is the perturbation function along the propagation direction, and $\Delta\beta = (\beta_2 - \beta_1)/2$ is the propagation constant mismatch between the coupled modes. For a conventional micron-scale optical waveguide with scattering perturbation, the right integral term equals zero over a long distance. The coefficient $\kappa^2/\beta^2 = n^2/N^2 - 1$ of low-order modes is also rather small because their effective index is smaller but very close to the refractive index of the guided layer. The result is that the inter- and intramode coupling is rather weak in uniform thin dielectric waveguides. Therefore, periodic perturbation would be necessary for efficient coupling of two different order guided modes over long propagating length. Usually, only short m lines can be observed because of mode coupling induced by scattering in the guided layer, see Fig. 4(b).

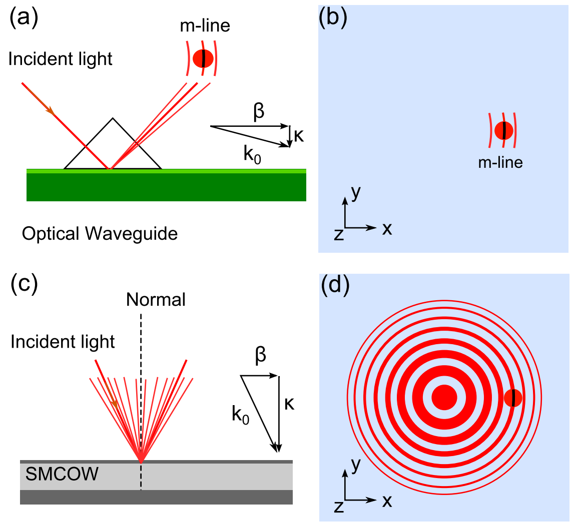

Fig. 4. Excitation of the m line in an all-dielectric waveguide and SMCOW. (a) Prism coupling of light into a thin dielectric optical waveguide. (b) A multiple short m line occurs when there is coupling among different guided modes due to light scattering. (c) Light coupling into SMCOW by means of the free-space coupling technique. (d) The conical reflection pattern of SMCOW, which is actually closed m-line circles.

The coefficient κ^2/β^2 of ultrahigh-order modes, on the other hand, is orders of magnitude larger, since their effective index approaches to zero. The mode coupling between ultrahigh-order modes is greatly enhanced; therefore, it noticeably reduces the coupling length ($L_c \approx \pi/\kappa$). Hence, the coupling length is small compared with the longitudinal phase matching length ($L = \pi/\Delta\beta$) of the two coupled modes, and it is thus reasonable to denote the perturbation by a $\delta(\vec{r})$ function in the modeling, where $\vec{r}$ is in the x–y plane. In this case, the coupling of ultrahigh-order guided modes can be calculated as

$$\kappa_c = \frac{\kappa^2}{\beta^2 \Lambda \omega_{\mathrm{eff}}} \left| \int R\delta(\vec{r}) e^{i2\Delta\beta\vec{r}} \mathrm{d}\vec{r} \right| = \frac{\kappa^2 R}{\beta^2 \Lambda \omega_{\mathrm{eff}}}, \tag{3}$$

where R is a defined parameter including total scattering perturbation and is of order unity. Since the waveguide is uniform, R is considered to be constant accordingly. $\Lambda = L$ is an abstract effective perturbation period. Mode coupling is thought to be complete in a length much shorter than Λ. Equation (3) suggests that coupling among all mode orders and in all directions is possible without periodic perturbation for ultrahigh-order guided modes, see Fig. 4(d).

Based on the above discussion, the mechanism of the conical reflection of SMCOW can be interpreted as the outleakage of omnidirectional propagating ultrahigh-order guided modes. The light incident on the SMCOW at a phase matching angle excites one of the high-order guided modes. This excited mode couples into all directions of the same order and with other mode orders. Finally, the strong coupling effect redistributes the energy almost evenly among each guided mode. The outcoupling light forms conical radiation, which produces the received concentric-ring pattern.

4. CONCLUSION

In conclusion, we have observe extraordinary conical reflection of light by a three-layered planar SMCOW. Each layer of the waveguide is uniform with no microperiodic structure embedded. The multiple conical reflection occurs at the critical angles predicted by the guided mode excitation condition. According to the *m*-line spectrum, the obtained result is a direct indication of the excitation of omnidirectional ultrahigh-order guided modes. The intensity of the omnidirectional guided mode is even in all directions due to strong mode coupling.

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