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Multi-duplication beam source for virtual reality-head mounted display under leaky mode resonance

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Abstract:
We realized a multi-duplication of the emission beam generated at the surface by using the excitation of the leaky mode in a TiO$_2$ slanted nanograting layer. In the TiO$_2$ layer, the beam is waveguided along the short-axis direction of the grating at a specific injection angle $\Theta$. On the surface of the layer, a beam consisting of leakage generated during the waveguide is emitted. The emitted beam would have a high optical intensity compared with the general emission. Furthermore, it would generate an afterimage for the waveguide direction. In this work, we performed angle-resolved measurements to obtain two effects, namely intensity improvement and afterimaging. Subsequently, we identified an appropriate resonance condition for the above leaky radiation on the 1D waveguide on the surface. Thereby, the resonance peak for the leaky waveguide with $\Theta_{\text{FWHM}} = 8.0-10.0^\circ$ at $\Theta = 10^\circ$ was verified in the measurement. This grating sample is likely to be effective as a novel coupler on a binocular virtual reality (VR) head-mounted display (HMD) based on multiduplication broadband beam emission.

Keywords; leaky mode, resonance, asymmetry, multi-duplication TiO$_2$, slant grating, VR
1. Introduction

Recently, projection instruments such as virtual reality (VR) head-mounted displays (HMDs) consisting of three components (light source, coupler, and display) have attracted the attention of many users. The HMD is worn on the head, and the user can see the VR image in front of the eye. In this case, an HMD designed to cover the eye makes it convenient for the user to perceive immersion [hmd]. Typical VR-HMDs include Quest (Oculus) [1], VIVE (HTC) [2], and M-300 smart glass (Vuzix) [3]. Devices based on these have been applied to games, simulators, and watching of sports. Among these, waveguide VR-HMD such as Quest (Oculus) are now popular with customers because these display high performance and compact design [w1][w2].

![Figure 1](image)

In this work, we recommended the provision of an afterVR image with high performance (see Fig. 1(a)) as a new attempt for the waveguide VR-HMD. One of the purposes of this study was to provide a speedy image with afterVR. We expect to provide users with an illusion of time flow by providing an afterVR image in front of the eye.

To obtain such afterVR images, it is necessary to duplicate the VR images multiplied along one direction using the TiO$_2$ slanted nanograting sample. In this work, we did not duplicate images four or five times as performed earlier [es]. Rather, we focused on developing a leaky propagation mode [Ushi][99%][sens][guide][11][12][13][14][15][16] to duplicate images at more than two digit levels. A leaky propagation mode is a propagation model that generates resonant-gratings with nanometer-order thickness. This results in multi-diffraction in a surface with multi-reflection in a slab. Therefore, if the waveguide layer becomes thin, the number of optical collisions at the surface of the slab should be increased. The number of emission beams is secured sufficiently with this effect. The obtained emission beam is also likely to exhibit high-power characteristics [99%] and phase modulation [sens][guide].

Several studies have been conducted in the leaky mode using gratings [11][12][13][14][15]. Among these, studies on guided-mode resonance (GMR) sensors using leaky waveguides [sens] and leaky-wave antennas (LWA) on bull-eye structures are noteworthy [16]. In GMR sensors, the relationship between phase shift and dielectric variation enables the detection of highly sensitive wavelength and phase shifts [sens]. In bull-eye LWA, the bull-eye structure supports the
omnidirectional (360°) emission of leaky-wave beams [16]. These studies provided knowledge of basic and applied leaky waveguides.

To our knowledge, a few researchers have reported improvements in optical efficiency and expansion of field-of-view (FOV) with high-order diffraction imaging on a grating coupler [smally]. However, the investigation of the optimization of these elements under a leaky resonant mode is insufficient.

In this study, we investigated the resonance peak of the leaky propagation mode generated in a SiO$_2$ embedded-TiO$_2$ slanted grating layer [ao][es]. It was fabricated using electron beam lithography (EBL) [bai], reactive ion etching (RIE) [bai], and electron beam deposition (EBD) [bai][oga]. Specifically, we theoretically and experimentally comprehended the leaky resonance for incident angle resolution in the TiO$_2$ layer. Resonance is generally acknowledged to be sensitive to the injection angle (or wavelength) in an optical leaky resonance mode. Therefore, we first attempted to identify the resonance peak in a leaky driving mode. It enhances the beam intensity by the sweeping angle (or wavelength) of the incident beam. Next, we verified the beams emitted on a grating sample at the resonance angle with the naked eye and then, analyzed these. Finally, we fabricated a prototype of afterVR-HMD using multiple emission beams.

Fig. 1(b) shows the entire configuration of a leaky drive-type VR-HMD as a development objective. As a leaky optical configuration, the coupling efficiency is low. However, the design for an HMD is convenient [des][des2]. Therefore, this transmission optical configuration was adopted. In this study, we anticipated the emergence of a two-directional propagation mode using the TiO$_2$ coverage region. As mentioned above, the number of optical collisions at the surface of the waveguide increases if a leaky mode is formed in a thin TiO$_2$ layer. This supports the generation of multiplication beams. The obtained multiplicated beams should also create sidebands for the original diffraction. After beam duplication, we attempted to fabricate an optical bridge connecting another coupler sample (Gr2) to a display. This fabrication process is straightforward if optical refraction phenomena are used. Meanwhile, the process is complex if frustrated-TIR [ftir] phenomena are used as proposed in Ref.[es]. In this study, we anticipated that the obtained two-way duplication beams would create VR images with sidebands over the Gr samples.

Fig. 1(c) illustrates a 3D-viewer model that shows how a user can see VR images when he/she wears HMD Google. In this study, a TiO$_2$ dielectric layer was used as the waveguide material. Thereby, this system enabled the emission of afterVR images with high continuity. Afterimages were displayed through waveguide glass on the user’s gaze. These images are suitable for the binocular model. Additional technical advantages such as intensity balancing and phase-shift effects are also likely.

2. Model for waveguide launcher

![Figure 2](image)

**Figure 2** Twin waveguide launcher model

The periodicity, height, width, slant angle of gratings, and thickness of TiO$_2$ are $\Lambda=704$ nm, $d=230$ nm, $w=200$ nm, $\varphi=55^\circ$, and $h=920$ nm.

Fig. 2 shows scanning electron microscopy (SEM) images of the waveguide launcher consisting of the coupler sample fabricated previously. The details of the sample preparation are reported in [ao][es]. Therefore, we do not mention it here. In Fig. 2, the wave vectors and waveguide patterns are indicated by arrows.

Here, we explain the likely beam-duplication mechanism on the grating coupler. A resonance peak for the leaky mode in the grating sample can be observed by sweeping a beam ($k_a$) as a function of the incident angle $\Theta$ on the SiO$_2$/TiO$_2$ grating coupler. A layer of the resonant grating as shown in Fig. 2 accept to formation of a zigzag waveguide lane composed of $-2^{nd}$ and $+1^{st}$ diffraction rays. At the grating surface, the TiO$_2$ layer emits a launcher to emit duplicate beams into the SiO$_2$ layer. That is,
waveguide beams passing through the grating can be emitted to the outside \( k_{\text{out}} \).

In this study, we investigated the emergence of a leaky mode on an embedded grating. Theoretical calculations and laser spectroscopy were performed on the proposed model to determine whether a leaky emission pattern exists.

### 3. Theoretical calculation

#### 3.1. Calculation model

![Theoretical model under leaky mode](image)

The total electric fields \( T_{-2} \) and \( T_{+1} \) of the transmitted beam are given as follows by adding the electric fields for the -2\(^{\text{nd}}\) and +1\(^{\text{st}}\) order diffraction rays generated at the grating surface:

\[
T = \sum_{N=0} n_{\text{eff}} \exp \left[ i \omega t - (N - 1)(\Phi_s + \Phi_f + 2k_wd) \right]
\]

Here, \( N \) is the number of surface collisions; \( n_{\text{eff}} \) is the effective refractive index under the condition of a phase mismatch on the grating layer; and \( \Phi_s \) and \( \Phi_f \) are the phase mismatches generated at the back and front surfaces, respectively. The effective refractive index \( n_{\text{eff}} \) can be expressed as follows using the periodicity \( \Lambda \), wavelength \( \lambda \), and incident angle \( \Theta \):

\[
k_w = k_0 (n_{\text{SiO}_2}^2 - n_{\text{eff}}^2)^{1/2}
\]

\[
n_{\text{eff}} = n_{\text{SiO}_2} \sin \theta_i + \frac{m \lambda}{\Lambda}
\]

According to these equations, the intensity of the multi-duplication beam depends strongly on the collision number \( N \), grating height \( d \), and phase difference \( \Phi \). Hence, to search for a leaky resonance angle \( \Theta_{\text{res}} \) using the angle sweeping technique, we need to consider the field enhancement effect by increasing the collision numbers \( N \) depending on the grating layer thickness \( h \) and degree of phase differences \( \Phi_f, \Phi_s \).
3.2. Field calculation

In addition, the electric field distribution for the cross-section of the TiO$_2$ dielectric layer was analyzed using finite-difference time-domain (FDTD) simulation software. Fig. 4(a) shows the optical configuration condition using the following parameter settings: wavelength of injection beam ($\lambda$) = 532 nm; polarization: TE; diameter (D) = 5 $\mu$m; beam profile: Gaussian profile; simulation time (t) = 25 fs; mesh step (s) < 50 nm; and boundary conditions: perfect matching layer (PML).

First, we calculated the electric fields in the cross-section of the TiO$_2$ layer as a function of the incident angle $\Theta$. According to the data in Fig. 4(b), there are four types of waves with different amplifications in the marked positions (+, +++, --) at $\Theta = \pm 10^\circ$. This indicates the presence of counter-propagating light in the thin layer of TiO$_2$ at the leaky resonant angle $\Theta_{res}$ for this sample.

Fig. 4(c) shows the degree of leaky propagation loss when the thickness of the TiO$_2$ layer (h) varied. Thus, the thinner the TiO$_2$ layer, the more effective is the increase in the number of optical collisions (N). Thereby, the propagation loss decreases. However, certain negative factors can be
sustained straightforwardly if the thickness is excessively marginal. This is apparent in the cases of \( h = 460 \) and 620 nm. Thus, we concluded that \( h = 920 \) nm is suitable for this study.

Fig. 4(d) shows the field profile of the cross-section of the sample at resonance. Because the calculated electric fields showed a corrugated pattern composed of optical density at positive (+) and negative (-) for the edge sides in the \(+x\)- and \(-x\)-directions (see Fig. 4(f) and 4(g)), we concluded that the leaky waveguide is performed in a thin layer.

Next, far-field analysis was performed (as shown in Fig. 4(g)) to verify the beam emissions in the leaky resonance mode. As shown in Fig. 4(g), the emission intensity at -25° was four times higher than that at 38°. Furthermore, the size of the beam spots showed a marginal extension along the \( x \)-direction. We also observe that the intensity of the emitted beams was asymmetric because the grating had an asymmetric slanted shape. Fig. 4(i) and 4(h) show the expanding images for each field \(|E_{-2}| \) and \(|E_{+1}|\) in the far field. Each electric field was maximized at approximately \( \Theta = 10° \). Thus, these data show that the leaky resonant structure caused the beam to be launched. In addition, we observed that the full width at half maximum (FWHM) for the intensity peak of \(|E_{-2}|\) was \( \Theta_{\text{FWHM}} \approx 10° \) at \( \Theta_{\text{res}} = 10° \).

The obtained fact implies that the thin layer and the surface nano-periodic structure of TiO\(_2\) play the roles of optical waveguide and beam launcher, respectively. A twin beam launcher system with asymmetric amplification and phase damping effects was also fabricated.

4. Result and discussion

4.1. Angle-resolved measurement

![Diagram of optical configuration and observed images](image)

**Figure 5** Angle-resolved measurement for leaky mode analysis
(a) Optical configuration, (b) observed images for beam spots as a function of \( \Theta \). Left side; -2\( ^{nd} \), right side; +1\( ^{st} \) diffraction beam spots. (c) resonance peak for leaky propagation obtained by sweeping injection angle. Vertical axis; beam intensity, horizontal axis; (resonance – incident) angle \( \Delta\Theta \) (deg), dotted; polynomial curve to guide readers eye, I, III) at non-resonance, II) at a resonant angle.
Fig. 5(a) shows the optical configuration of the angle-resolved measurements of the sample. The TE polarized beam with $\lambda = 532$ nm passes through the polarizer (P), aperture (AP), mirror (M), beam splitter (BS), and prism (Pr). Then, the beam penetrates from the rear side of the Gr sample mounted on Pr. The -2$^{nd}$ and +1$^{st}$-order diffraction rays should form zigzag waveguides consisting of multiple reflections in a TiO$_2$ layer and permit the generation of propagation leakage to an SiO$_2$ layer (i.e., leaky propagation). Their beams enable these to emit to the exterior of a SiO$_2$ substrate as multiduplication beams. In this experiment, we attempted to observe duplication beams with asymmetric intensity in the far-field to verify the presence of leaky emission at the surface of the TiO$_2$ layer. (Note that we cannot directly experiment with the leaky mode in a layer because there is no way.)

Fig. 5(b) shows images of the -2$^{nd}$ and +1$^{st}$ diffraction beam spots. The intensity and spot shape of the beams appear to be marginally enhanced and blurred in the x-direction. Although these two beam spots seem to be extended to x-direction, it is because the diffraction angle $0^\circ$ at the Gr surface was expanded to the waveguide direction ($\theta_d \neq \theta_0$) [dife].

Fig. 5(c) shows the diffraction intensity (I) as a function of the incident angle ($\Theta$). The top and bottom figures show the data for the 2$^{nd}$- and +1$^{st}$-order diffraction, respectively. It is important to determine the outcomes of (I), (II), and (III).

1. At $\Theta \approx +6^\circ$, the intensity of the beams was significantly weak at the noise level.
2. At $\Theta = 10^\circ$, the intensity of the beams was significantly high and related to $|E_{-2nd}|:|E_{+1st}| = 7:4$. Owing to the rapid increase in I, leaky resonance for the TiO$_2$ layer should exist.
3. At $\Theta \approx +14^\circ$, the intensity for the beams was significantly low.

Consequently, the data in Fig. 5(c) show a broad peak at the resonance angle $\Theta_{res}$. The results obtained are closer to the calculation results shown in Fig. 4(h) and 4(i).

The full width at half maximum (FWHM) for the resonance in the diffraction leaky mode was $\Theta_{FWHM} \sim 8-10^\circ$. These experimental data nearly correspond to the simulation data, as shown in Fig. 4(h) and 4(i). In general, the linewidth of the FWHM for leaky diffraction is comparably narrow, and its value should be less than 0.5 $^\circ$. However, if there is an imperfection in the sample structure (including deflection or defects), it may modify the resonance condition. This would result in a broadening of the resonance peak.

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As illustrated in Fig. 6(c), the line profile showed that the maximum optical efficiency for the -2$^{nd}$-order diffraction beam was 30%. However, owing to the optical absorption originating from surface roughness, the gain after emission reduced by approximately 10%. In addition, sideband
emission was verified on the right side of the emission beam as well as at the top of Section 4.1.

4.2. VR imaging (on benchtop)

Fig. 7 shows the test results for VR-HMD imaging. We observed a VR image developed over the WG by adding an output grating coupler (Gr2) on the opposite side of Gr1.

Fig. 7 shows the results of the ray tracing simulation for the HMD model. After the beam diffracted by Gr1 is guided by TIR in the WG, the diffracted beam is re-diffracted at Gr2 with a divergence angle $\Theta_{\text{div}} > 5.7^\circ$. Then, it is projected in front of a screen (Sc) position corresponding to the position of the eye box. On an Sc, we can observe a beam spot group with uniformity. This implies that the beam quality is preserved before and after the waveguiding in the WG. Meanwhile, information for leaky waveguides is difficult to verify because Tracepro simulation software cannot address microscopic data. Consequently, we verified that the waveguiding path for VR imaging had been simulated effectively.

Fig. 7(b) shows the experimental setup and VR image results. The optical path reproduced the flow of $\text{LS} \Rightarrow (\text{M} \Rightarrow \text{DM} \Rightarrow \text{P} \Rightarrow \text{SP}) \Rightarrow \text{Pr} \Rightarrow \text{C1} \Rightarrow \text{WG} \Rightarrow \text{C2} \Rightarrow \text{Sc}$, as described in the simulation. We set a camera at the Sc position and then, created the aerial VR image to the origami position in front of the board position.

According to Fig. 7(c), a line-shaped aerial VR image with a sideband was observed. It was floating in the focal plane similarly as an origami object (O). From this result, we can conclude that an afterVR-HMD prototype was fabricated.
Appendix

A. Prototype of wearable VR-HMD

A1. VR imaging (on device)

In addition, we transferred the VR HMD from the benchtop type to the wearable type.

Fig. A(a) shows the optical configuration for a wearable VR-HMD. The basic optical configuration is identical to the benchtop configuration. However, the entire length of the optical path is miniaturized. In addition, the position of the eye box is adjusted with an assumption while wearing this HMD.

Fig. A(b) shows the 3D viewer for capturing a VR image floated in front at $L = 50$ mm from the waveguide display. Figure A(c) shows the observed VR image. From the observed photograph, we verified that the image is extended in the y-direction with intensity graduation. This data shows the leaky waveguide launcher as referred in [nc], and this is one of the proofs that VR image is duplicated multiply one-dimensionally.

Fig. A(d) shows the 3D viewer overlapping a VR image with the object. Fig. A(d) shows the result of the image observation. From the observed image, we determined that the VR image position is on the same focal plane as the O position. According to the analysis result, the area intensity profile indicated the intensity gradient extending in the y-direction. Furthermore, the line profile also indicated a similar gradient. Although the edge response for the x-direction does not have a difference well, the one for the y-direction has a large difference. Thus, we can state that the VR image obtained has the intensity gradient (gradation) along the $+y$ direction. It is interpreted to be a result of the 1D multi-duplication phenomena occurring from the leaky wave.
A2. Viewpoint shift of VR image

Figure A2 Viewpoint shift contribution; (a) right direction (φ ~ +5°), (b) left direction (φ ~ -5°) viewpoint observation configuration, (i-iv) observed VR images. Right side inset; expanded image showing image shift and illustration showing perspective transformation.

Next, we verified the perspective shift of the VR image (see Fig. A2) to investigate the viewing range for VR. When the user viewed the VR image from the right-hand side (φ ~ +5°), the image was observed on the left-hand side of the photograph. In contrast, when the user viewed the image from the left-hand side (φ ~ -5°), the image position was shifted to the right-hand side of the photograph. This result revealed that the VR image position is at the object’s focal position, which causes the shift in perspective. The result obtained corresponds to that for the perspective shifting VR image on the paper [view]. However, we could not find a VR image at φ < -5° and φ > 5°. Therefore, we can state that the range of perspective shift is restricted.

In addition, we highlight the perspective transformation of VR images during perspective shifting. As illustrated on the right side of Fig. A2, a thin trapezoidal image is observed when we observe it from the right-hand side. The shape of the image approaches a square when the perspective is shifted to the left-hand side. Then, when we observe from the left-hand side, an inverted thin trapezoidal image is observed. This result indicates that the orientation of the image has varied. This implies that a perspective transformation occurs.

Conclusion

We succeeded in creating afterVR images using beams emitted in two directions by the SiO2 embedded TiO2 grating coupler. The mechanism for the afterVR image appeared to be a multi-duplication of the VR image originating from leaky resonance. At resonance, the field ratio for the emission beams had the following relationship: |E_{-2nd}|:|E_{+1st}| = 7:4. Furthermore, their beams created short afterimages in one direction. Moreover, owing to the deflection and defects on the sample surface, the FWHM of the resonance peaks for the two emissions had Θ_{FWHM} = 10° at Θ = 10° unless the resonance peak was normally significantly narrow. In the future, this sample would be a good coupler for developing an afterVR-HMD with high performance.

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