Analytical modeling for eliminating the 0th order by a tantalum oxide ridges grating

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In this paper, using rigorous coupled-wave analysis, a beam splitter for eliminating 0th order by tantalum oxide ridges grating is proposed. The grating has a thinner structure of tantalum oxide grating ridges. At a normal incident light of λ=1550 nm, the grating can achieve the high efficiencies of the ±1st orders of 48.79%, 48.18% for transverse electric, transverse magnetic polarization and the 0th order of less than 1% for both polarizations. Besides, the grating has not only a good manufacturing tolerance in grating period *d* and duty cycle *f* but also a wide spectral bandwidth of 60 nm.

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1. Introduction

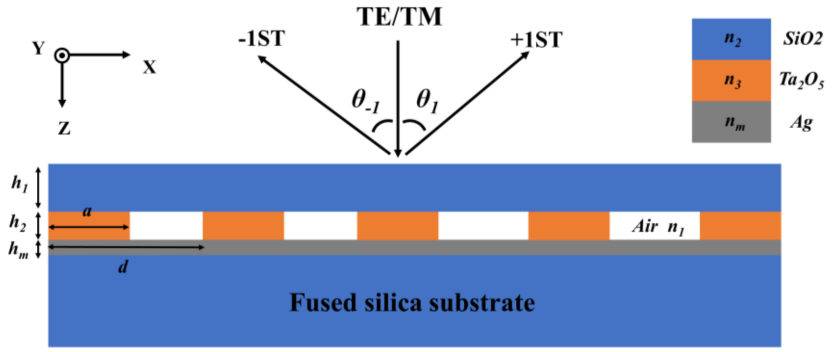
Grating is an optical device composed of a large number of parallel slits with equal width and spacing. With the increasing demand for micro-nano optical device, grating becomes an important optical diffraction device and the focus of research, which can be found in various optical applications, such as photoelectric sensor [1, 2], photoelectric coupler [3, 4], photorefractive filter [5, 6], metamaterial absorber [7, 8] and so on. According to requirements, people design gratings with different functions such as polarizing [9], light splitting [10, 11] and chromatic dispersion [12, 13]. Beam splitter [14-16] is an important optical element, which can separate incident light into several beams. Traditional beam splitters are based on the birefringence of crystals [17]. The defect of these beam splitters is their large size. It is not in line with the development of science and technology. Due to the advantage of high integration and stable optical performance, grating is suitable to function as a beam splitter. Wang et al. described a polarization-selective beam splitter by a sandwiched grating, which can fulfill the high efficiency element for TE polarization and the two-port output for TM polarization [18]. Yang et al. proposed a novel broadband beam splitter (BS) at a wavelength of 1550 nm [19]. Lin et al. presented a polarization-independent highly-efficient transmission beam splitter based on the cross-shaped ridge structure [20]. Using material whose refractive index is high to manufacture grating can enhance the diffraction efficiency of grating. Tantalum oxide (Ta_2O_5) is a suitable material with low absorption and high refractive index [6, 21].

Compared to the past, the density of grating has increased. To analysis the diffraction characteristics of high-density grating, vector diffraction theories [22,23] which includes rigorous coupled-wave analysis (RCWA) [24,25], finite element method (FEM) [26,27], and so on are important. RCWA is a method that can give exact vector solutions of grating diffraction electromagnetic field in incident, grating and transmission regions. In the optimization of grating structure parameters, the process of the optimization needs much time. It is necessary that simulated annealing (SA) [16], an algorithm that can randomly find the global optimal solution of the objective function in the solution space under the jump characteristics of probability, is introduced to accelerate the optimization.

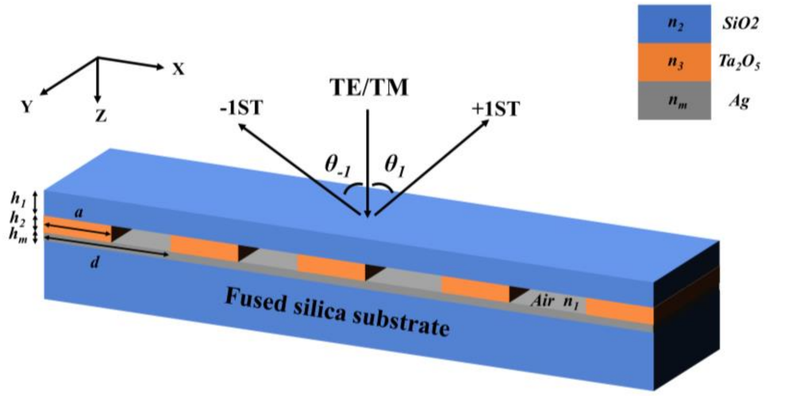
A beam splitter for eliminating 0th order by tantalum oxide ridges grating under the normal incident light of wavelength 1550 nm is introduced in this paper. Using RCWA and SA, the parameters of structure can be obtained to achieve the objective function where the incident light is coupled to ±1st orders with a diffraction of more than 48% uniformly, and the 0th order is less than 1%, and the efficiencies of transverse electric (TE) and transverse magnetic (TM) polarizations can be calculated. For the accuracy of the result by RCWA, FEM is introduced to verify the result. The structure of grating in this paper is based on Ref. [27]. Comparing with Ref. [27], the thickness of proposed grating is thicker, but the diffraction performance is much better. What's more, the proposed grating also has a good fabrication tolerance. It confident that such a high-efficiency grating will has wide applications in the field of lithography and so on.

2. Structure design

Beam splitter has many types of structural schemes. Fig. 1 shows the schematic diagram of proposed grating. The up-bottom of the proposed grating is cover layer, periodic grating ridges, metal layer and substrate. Rooms between the grating ridges are grating groove which is full of air with the refractive index n_1=1.00. For substrate and cover layer, the structural material of them is fused silica, a hard, abrasion-resistant, and chemically stable material, of which refractive index of n_2=1.45. The material of metal layer is metal silver with the advantages of price and strong plasticity, of which refractive index of n_m=0.469−i*9.32. Tantalum oxide whose main constituent is Ta_2O_5 and refractive index is n_3=2.00 [21] is chosen as the material of the grating ridges, which is the most difference to Ref. [27]. All the refractive indexes are based on the wavelength of incident light λ=1550 nm. In addition, h_1, h_2 and h_m represent the thickness of cover layer, periodic grating ridges and metal layer, respectively. f, a, and d represent duty cycle, the width of grating ridges and grating period. f is defined as duty cycle which is the ratio of the width of the grating ridges a to the grating period d, which can be presented as $f=a/d$. The grating is illuminated by an incident light of λ=1550 nm at normal incidence (incident angle θ=0) from the incident region composed of air.



(a)



(b)

Fig. 1. The schematic diagram of the proposed grating: (a) 2-D view, (b) 3-D view (color online)

3. Optimization and discussions

Diffraction efficiency is important for beam splitter. The parameters of structure are the key to the efficiency. In order to achieve the optimized parameters of proposed grating, RCWA and SA are introduced in the optimization. RCWA is a vector diffraction theory calculating the efficiency of grating precisely. The simultaneous optimization is an intensive computational task, which need SA to accelerate the task. Based on Ref. [21], the thickness of metal layer h_m can be set as 0.100 μm. So, the parameters that should be optimized are h_1, h_2, f and d. The key equation is as follow:

$$\varphi(h_1, h_2, f, d) = \sum_\lambda[\left(1 - 2DE_{RTE(-1)}\right)^2 + \left(1 - 2DE_{RTM(-1)}\right)^2], \quad (1)$$

where $DE_{RTE(-1)}$ and $DE_{RTM(-1)}$ represent the efficiencies of the -1st order for TE and TM polarizations.

For the proposed grating in this paper, the efficiencies of the ±1st order are almost equal, so it just needs to calculate the -1st order. Based on Ref. [28], the period d should be set as $1\lambda \leq d \leq 2\lambda$ to realize only three diffraction orders. After the calculation, the results of optimization are h_1=0.550 μm, h_2=0.350 μm, f =0.350 and d=2.560 μm. The parameters of optimization are listed in Table 1. And the efficiencies of TE and TM polarizations are η_0^{TE}=0.09%, $\eta_{\pm1}^{TE}$=48.79%, η_0^{TM}=0.75% and $\eta_{\pm1}^{TM}$=48.18%, which shows the polarization-independent characteristic in the optimized parameters [29]. To verify the accuracy of the results, FEM is introduced to be the second verification. As can be seen in Fig. 2, the efficiency curves are highly consistent, which show the results and the parameters are reliable. And the efficiencies under the optimized parameters based on two methods are listed in Table 2.

Table 1. The optimized parameters of grating structure

f	d	h_1	h_2	h_m
0.350	2.560 μm	0.550 μm	0.350 μm	0.100 μm

Table 2. The efficiencies of grating under the optimized parameters based on RCWA and FEM

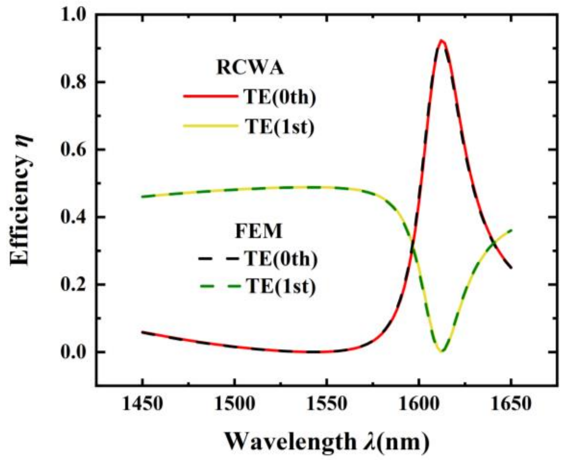
Theory	$\eta_{\pm1}^{TE}$ (%)	$\eta_{\pm1}^{TM}$ (%)	η_0^{TE} (%)	η_0^{TM} (%)
RCWA	48.79	48.18	0.09	0.75
FEM	48.73	48.17	0.09	0.65

Compared to the reported Ref. [27], in this paper, the efficiencies of ±1 orders for both polarizations are approximately similar, but the elimination of the 0th order is much better, the thickness of cover layer h_1 and periodic grating ridges h_2 are thicker. The data of the comparison is shown in Table 3.

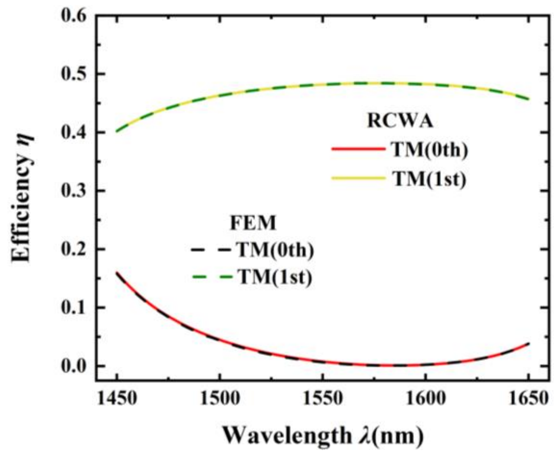
Table 3. Comparison of the thickness of cover layer and grating ridges between this work and reported Ref. [27]

	$\eta_{\pm1}^{TE/TM}$ (%)	$\eta_0^{TE/TM}$ (%)	h_1+h_2 (μm)
This paper	>48%	<1%	0.550+0.350
Ref. [27]	>48%	<1%	1.190+1.050

Fig. 3 shows the efficiency versus the thickness h_m of metal layer. When h_m is higher than 0.100 μm, the efficiency is hardly changing. So, in order to save cost in actual manufacture, the thickness h_m can set as 0.100 μm. Fig. 4 presents the normalized field intensity distribution of the proposed grating under two polarizations. It can be clearly seen that when the energy of both polarizations reaches metal layer, the energy is almost reflected back for ensuring the reflective effect. What's more, the two electric field figures describe that after the incident light is coupled in the grating, the beam splitting effect is obvious. Due to the grating structure is periodic, the energy distribution is also periodic.



(a)



(b)

Fig. 2. The comparison of spectra calculated by RCWA and FEM under the optimized parameters: (a) TE polarization, (b) TM polarization (color online)

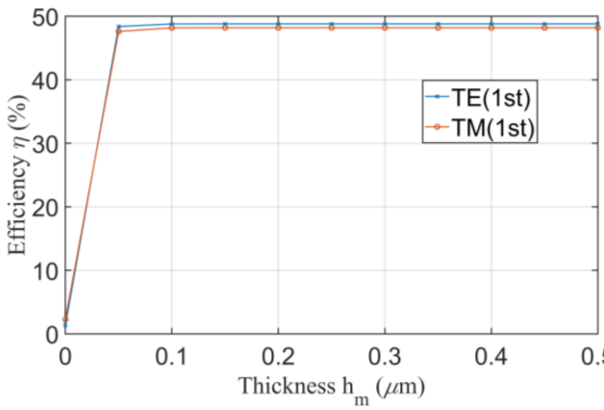


Fig. 3. The efficiency versus the thickness h_m of the metal layer under the optimized parameters (color online)

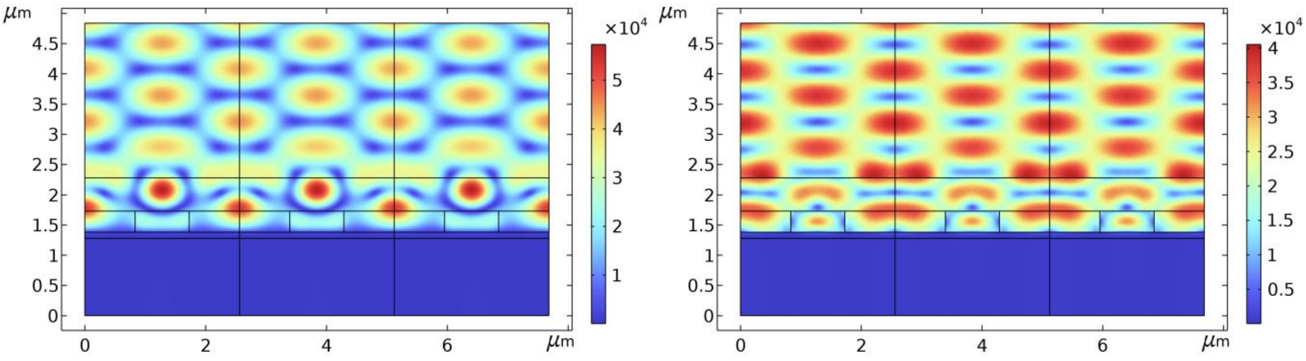


Fig. 4. The normalized electric field distribution diagram of the grating under the optimized parameters: (a) TE polarization; (b) TM polarization (color online)

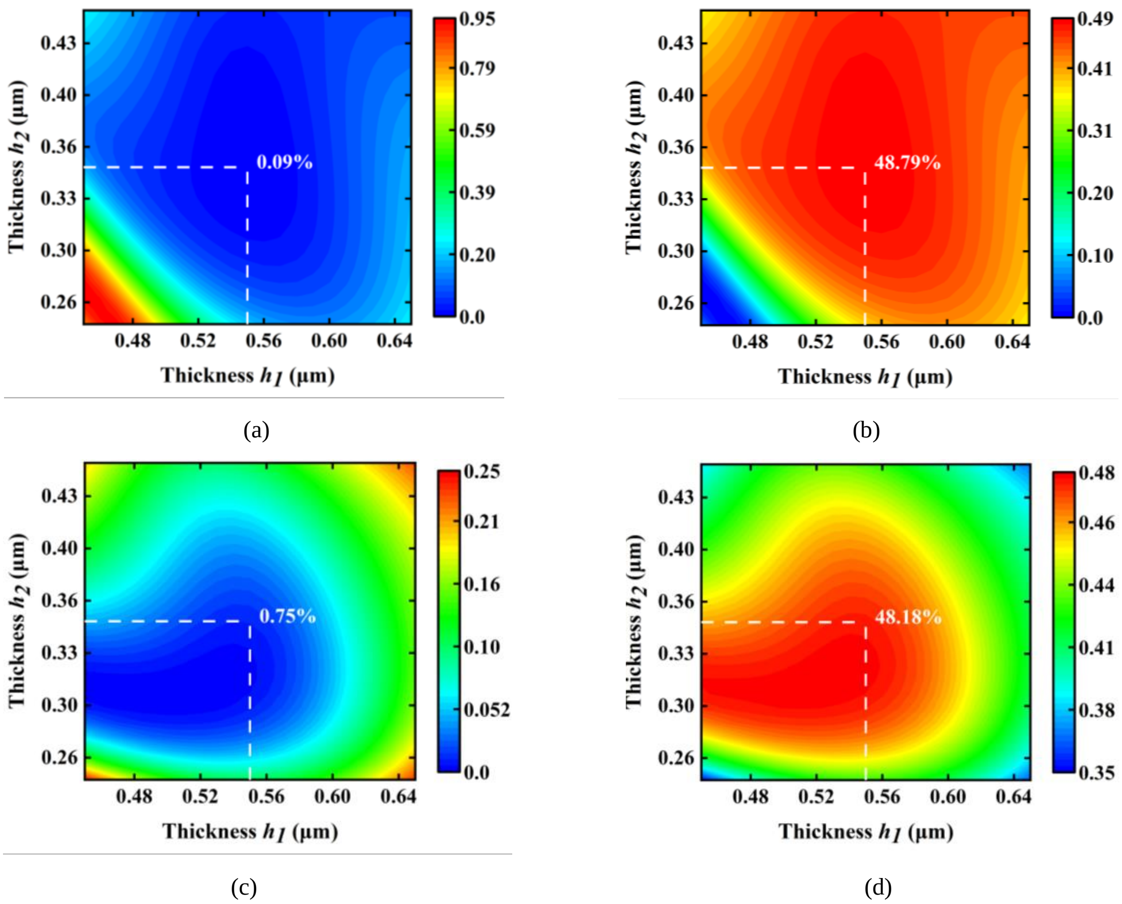


Fig. 5. The efficiency versus the thickness h_1 and h_2 of the cover layer and the grating ridges under the condition of λ=1.550 μm, d=2.560 μm, h_m=0.100 μm and f=0.350: (a) the 0th order of TE polarization; (b) the ±1st orders of TE polarization; (c) the 0th order of TM polarization; (d) the ± 1st orders of TM polarization (color online)

The propagation of the input light in the grating region and the phase difference of the coupled light wave is affected by the thickness of cover layer h_1 and the ridges h_2. Fig. 5 presents the efficiency versus the thickness h_1 and h_2 of cover layer and the grating ridges. For TE and TM polarizations, when the thicknesses of h_1, h_2 are h_1=0.550 μm, 0.320 μm< h_2<0.390 μm or h_2=0.350, 0.510 μm < h_1<0.580 μm, the efficiencies of the ± 1st and 0th orders at both polarizations are higher than 47% and less than 4%. In practical manufacturing, it is necessary to consider the fabrication tolerance in production process. Because the micro-optical devices are sensitive to the error of structure. In this paper, the grating period d and duty cycle f should be under consideration. Fig. 6 presents the efficiency versus the period *d*. It can be seen that for TE and TM polarizations, when the period *d* is in the range of 2.510-2.655 μm, the efficiencies of the ±1st and 0th orders are more than 47% and less than 3%. Fig. 7 presents the efficiency versus the duty cycle *f*. For two polarizations, when the duty cycle *f* is in the range of 0.284-0.532, the efficiencies of the ±1st and 0th orders are more than 47% and less than 3.5%. Over all, the results show the grating can maintain a high efficiency in the ±1st orders and a well elimination in 0th order, which represents the grating have excellent manufacturing tolerances in the thicknesses of $h_1$and h_2, the period *d* and the duty cycle *f*.

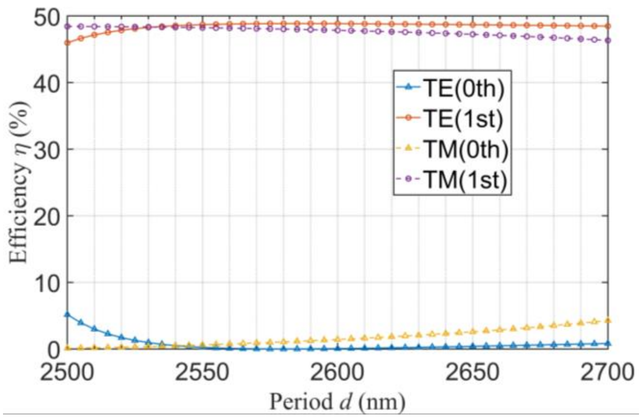


Fig. 6. The efficiency versus the period d under the condition of λ=1.550 μm, h_1=0.550 μm, h_2=0.350 μm, h_m=0.100 μm and f=0.350 (color online)

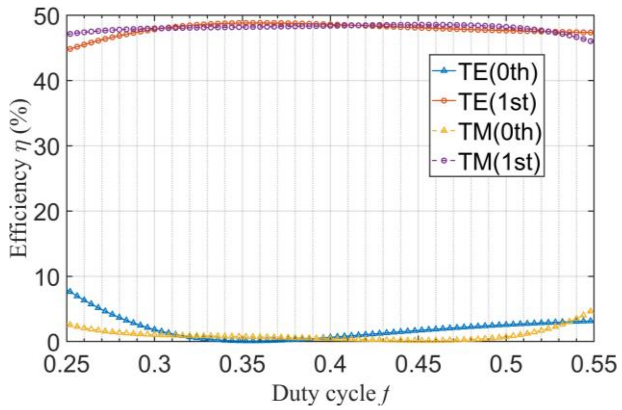


Fig. 7. The efficiency versus the duty cycle f under the condition of λ=1.550 μm, d=3.50 μm, h_1=0.550 μm, h_2=0.350 μm, and h_m=0.100 μm (color online)

In practical application, a wide bandwidth of incident wavelength is significant. Fig. 8 presents the efficiency versus the wavelength *λ* of incident light. It can be seen that when the wavelength *λ* is in the range of 1514-1574 nm (the bandwidth of 60 nm), for TE and TM polarizations, the efficiencies of the ±1st orders are all greater than 47%, also the 0th orders are less than 3%, which shows that it is at a well eliminated effect. Compared with the bandwidth of 31 nm in Ref. [27], the grating in this paper has an outstanding promotion in bandwidth and a better elimination in 0th order. The detail comparation is shown in Table 4. Fig. 9 presents the efficiency versus the incident angle θ. When the incident angle changes in the range of -2° to 2°, the efficiencies of ±1st orders are greater than 20%, and the efficiencies of 0th order have a great elimination. Keeping the incident angle in 0° can make the grating a good performance. All in all, the result shows the proposed grating has a wide bandwidth, which shows the it has a well stability in the actual application.

Table 4. Comparison of bandwidth of wavelength between this work and reported Ref. [27]

	Bandwidth of wavelength	$\eta_{\pm1}^{TE/TM}$ (%)	$\eta_0^{TE/TM}$ (%)
This work	1514-1574 nm (60 nm)	>47%	<3%
Ref. [27]	1532-1563 nm (31 nm)	>47%	<4%

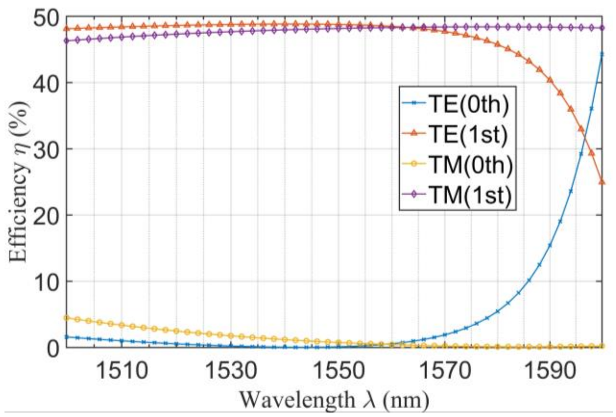


Fig. 8. The efficiency versus the wavelength λ of incident light under the condition of d=2.560 μm, h_1=0.550 μm, h_2=0.350 μm, h_m=0.100 μm and f=0.350 (color online)

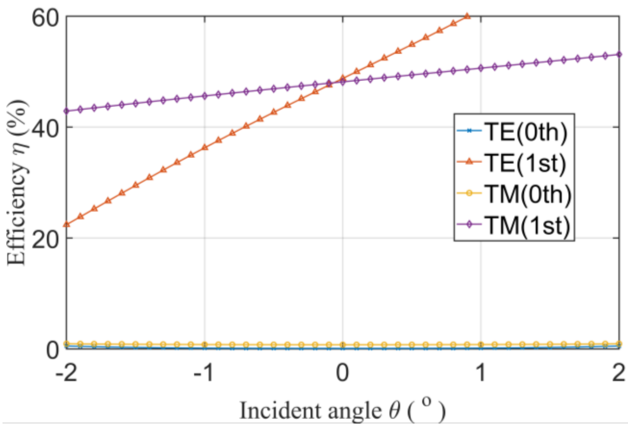


Fig. 9. The efficiency versus the incident angle θ under the optimized parameters (color online)

4. Conclusion

Over all, a beam splitter for eliminating 0th order by tantalum oxide ridges grating is proposed in this paper. The proposed grating is illuminated by a normal incident light of 1550 nm. Using the vector diffraction theory RCWA and algorithm SA, the optimized parameters of the structure of the grating can be achieved. Based on the calculation under the parameters, for TE or TM polarizations, the grating has the high efficiencies of the ±1st orders reaching 48.79% or 48.18%, and a well elimination in 0th order whose efficiency is 0.09% or 0.75% respectively. Compared to Ref. [27], the proposed grating has a similar performance, but a thinner structure. Besides, we have discussed the tolerance of the period *d* as well as the duty cycle *f* and the bandwidth of wavelength. Under the condition of 2.510 μm < d < 2.655 μm or 0.284 < *f* < 0.532 or 1514 nm < λ < 1574 nm, for both polarizations, the efficiencies of the ±1st orders and 0th order are more than 47% and less than 3.5%, which show that the proposed grating not only has the good tolerance in practical manufacturing but also a wide bandwidth of wavelength. It is confident that such an excellent performance grating can offers the grating which has similar structure or function reference value.

Acknowledgements

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