Simulation

畅星兆 11.22

衡量热电调制器的几个参数

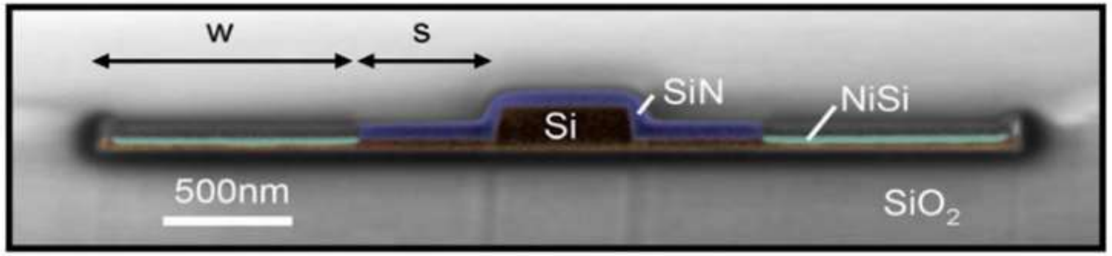
Table 1. Summary of recent thermo-optic waveguide phase shifter parameters where L is the total heater length, V_π and P_π are the applied voltage and power necessary to reach π radians of phase shift, respectively, and τ is the limiting rise or fall time constant. In results where τ is not reported, the single-pole approximation $\tau = \frac{0.35}{f_{3dB}}$ is used to convert between metrics.

	Material	Cladding	L (µ m)	Loss (dB)	V_π (V)	P_π (mW)	τ (μs)	$P_\pi \cdot \tau$ (mW·μs)
Here	SOI	SiO_2	61.6	0.23 dB	4.36	24.77	2.69	66.9
[10]	Si	Air	>9.42	0.5 dB	11.93	12.7	2.4	30.5
[12]	TiN in SOI	Air	1000	0.3 dB	0.86	0.49	144	70.5
[11]	NiSi in SOI	Air	200	5 dB	1	20	2.8	56
[17]	Cr-Au in SOI	SiO_2	700	32 dB	1.66	46	3.5	160
[14]	Ti in SOI	Air	100	8 dB	13.3	10.6	34.9	370
[16]	Metal in SOI	SiO_2	2500	< 12 dB	-	235	60	14100

-- 解释几个参数的意义

Harris, Nicholas C et al., Efficient, compact and low loss thermo-optic phase shifter in silicon, Optics express, 2014.

Ref 1



文献1

- 描述结构

  SOI, (两个变量)w = 1 um, s 0.1~4 um

- 描述材料
- 热源:

  NiSi通电

Table 1. Thermal Conductivities Used in Simulations

Material	κ ($W\ m^{-1}\ K^{-1}$)
Si (bulk)	150 [11]
Si (50 nm slab)	50 [11]
NiSi	50
SiO_2	1.27 [12]
Si_3N_4	2 [12]

slab: lower thermal conductivity due to phonon boundary scattering

Joris Van Campenhout et al., Integrated NiSi waveguide heaters for CMOS-compatible silicon thermo-optic devices, Optics Letters, 2010.

论文中的仿真工作

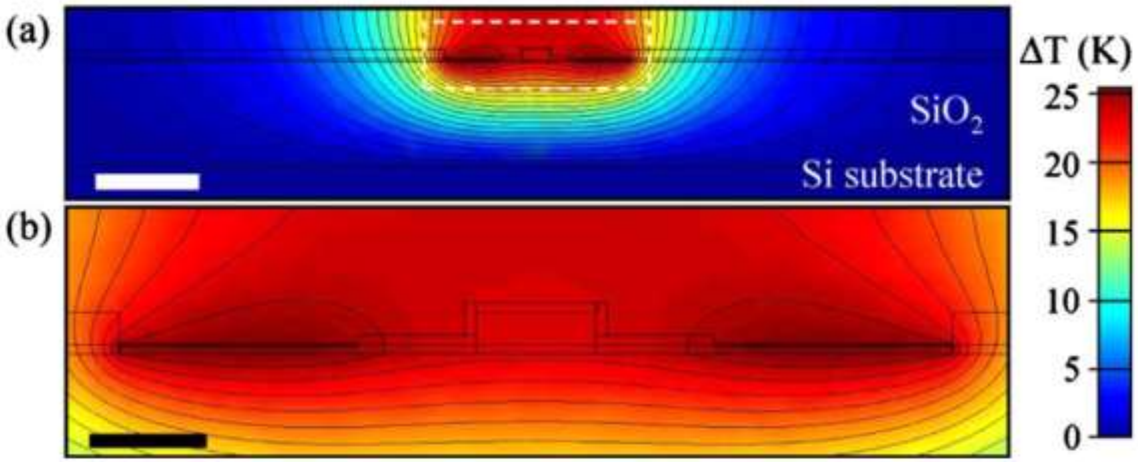


Fig. 4. (Color online) (a) Simulated 2-D distribution of the expected temperature increase (in kelvin) for 0.1 mW/μm power dissipation. The scale bar is 2 μm long. (b) Magnification of (a), showing a temperature increase in the waveguide core of 23 K. The scale bar is 500 nm long.

steady-state 2-D thermal simulation, 设定热源, 边界条件, 初始值, 求稳态解. (只有热学仿真)

热源: 面热源(2D图中为两条线)

$0.1mW/\mu m \rightarrow 10^8 W/m^2$ (如何推算的)

波导上方1um空气层

变量: w = 1 um, s = 0.5 um, 空气层厚度: 1um

结果: dt(waveguide) ~ 23K

ref

问题:

1. 功率的转换

$$0.1mW/\mu m \rightarrow 5\times 10^{7}W/m^{2}$$

2. 边界条件的确定
3. 结构不确定
4. 仿真区域大小

3类边界条件:

1. 第一类边界条件 规定了边界上的温度值
2. 第二类边界条件 规定了边界上的热流密度值
3. 第三类边界条件 规定了边界条件上表面传热系数以及外界温度

ref

初始仿真

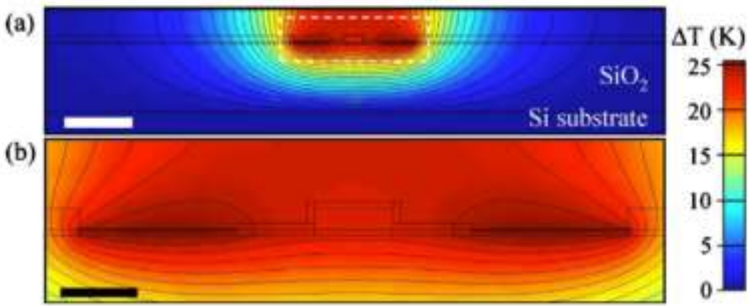
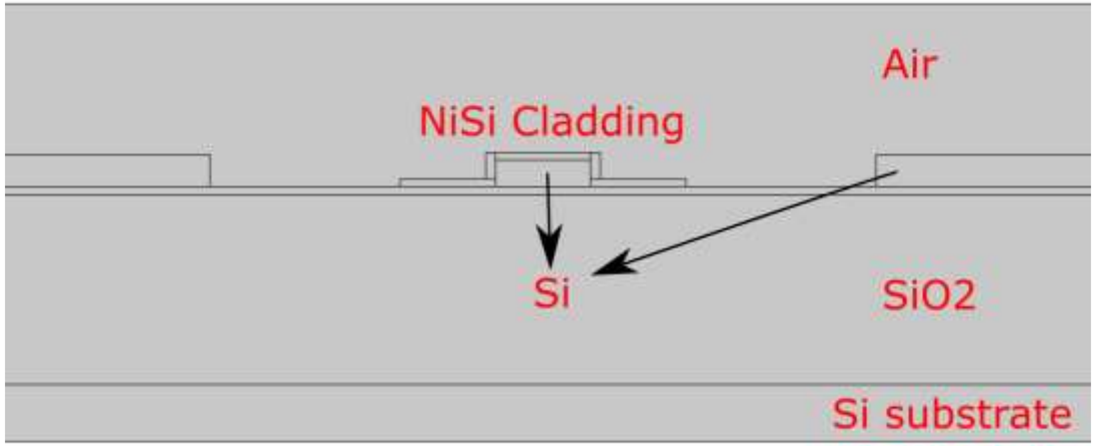


Fig. 4. (Color online) (a) Simulated 2-D distribution of the expected temperature increase (in kelvin) for 0.1 mW/μm power dissipation. The scale bar is 2 μm long. (b) Magnification of (a), showing a temperature increase in the waveguide core of 23 K. The scale bar is 500 nm long.



仿真结构图

仿真区域: [μm] 20 x 2.3 (w, h)

详述各个区域

NiSi Cladding: 0.05 μm

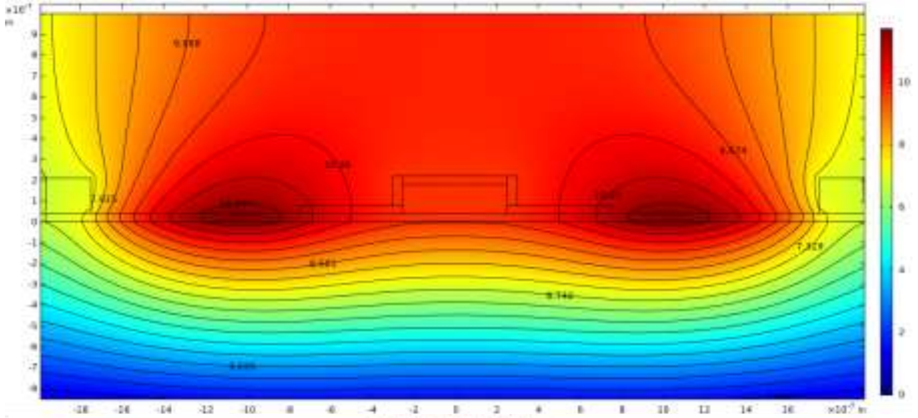
Si: 0.17 μm

SiO2: 2 μm (最开始用1 μm算的)

Si substrate: 0.5 μm(最开始用0.25 μm算的)

ref

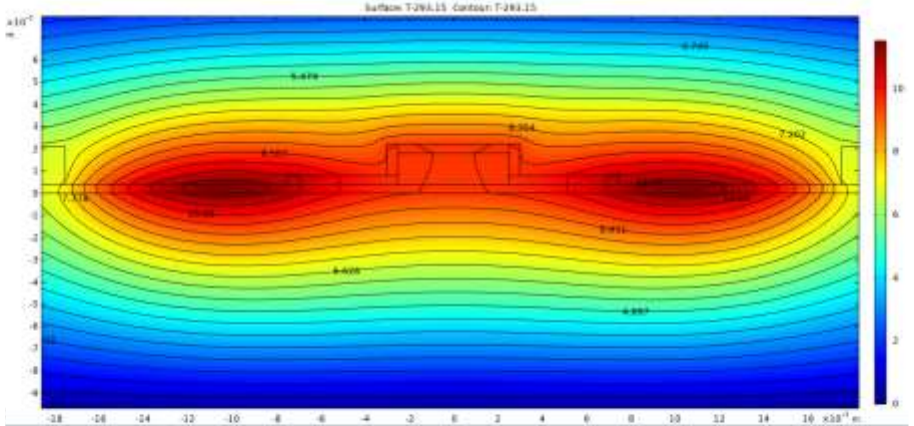
Buried Oxide Layer(SiO2) 减半时(错的)



左右下边界: T = 293.15 K

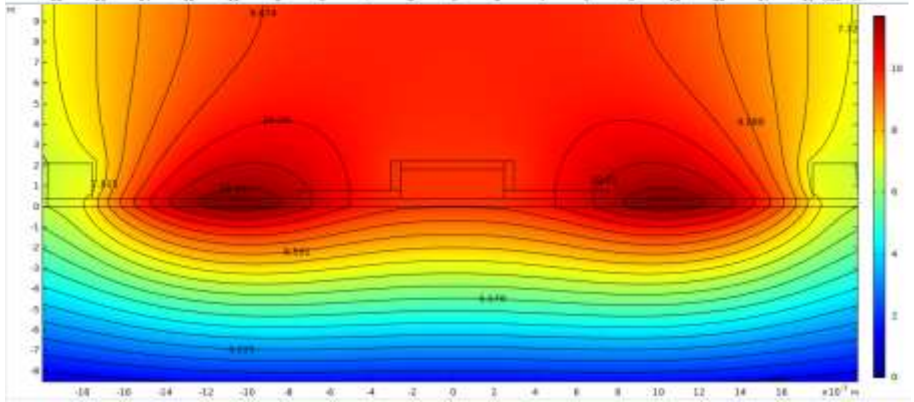
上边界: heat flux 热交换, T = 293.15 K, $h = 25\, W/(m^2 \cdot K)$

温度(波导中心): 302.87 K, d = 9.72 K



所有边界: T = 293.15 K

温度(波导中心): 302.65 K, d = 9.50 K



左右下边界: T = 293.15 K

上边界: heat flux 热交换, T = 293.15 K, $h = 5\, W/(m^2 \cdot K)$

温度(波导中心): 302.87 K, d = 9.72 K

对流换热系数

单位: $W/(m^2 \cdot K)$ 单位温差时的单位面积上的热通量

影响因素:

1.对流运动成因和流动状态

2.流体的物理性质(随种类、温度和压力而变化)

3.传热表面的形状, 尺寸和相对位置

4.流体有无相变(如气态与液态之间的转化)

对流换热系数的大致量级:

空气自然对流: 5 – 25

气体强制对流 20 ~ 300

水的自然对流 200 ~1000

水的强制对流 1000 ~ 15000

油类的强制对流 50 ~ 1500

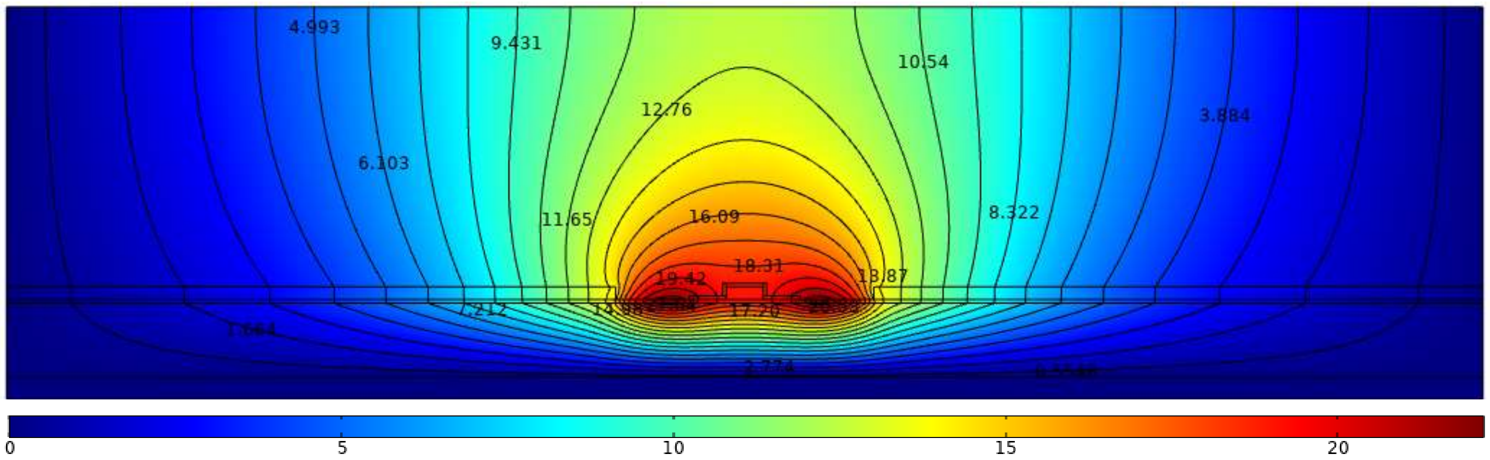
水蒸气的冷凝 5000 ~ 15000

有机蒸汽的冷凝 500 ~ 2000

水的沸腾 2500 ~ 25000

ref

当时排查原因, 还改变空气层厚度..



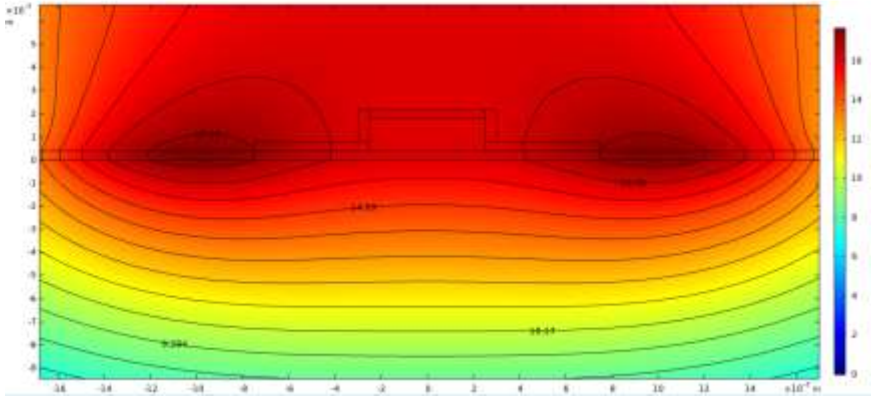
之后, 将空气层厚度从1μm变为4 μ m

边界条件相比上一个不变

左右下边界: temperature = initial value

上边界: heat flux 热交换, 假定边界外为初始温度的空气

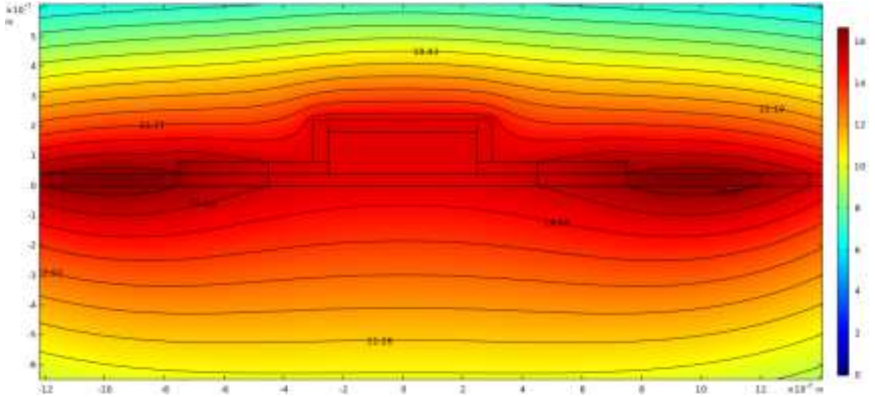
初始仿真结果(空气层厚度1 μm)



左右下边界: T = 293.15 K

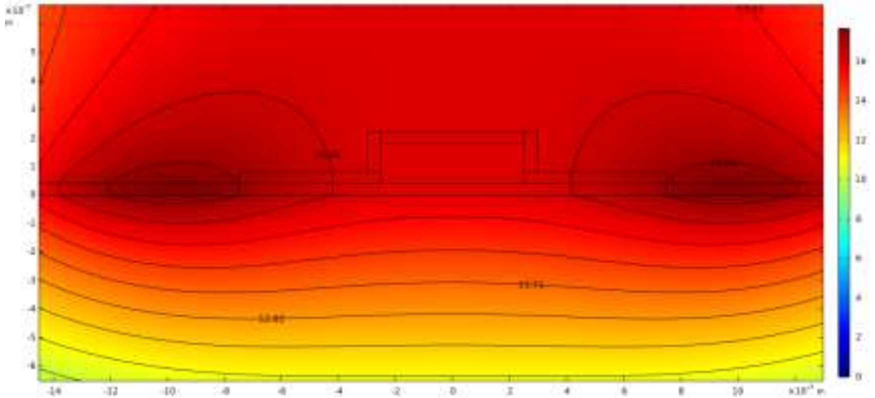
上边界: heat flux 热交换, T = 293.15 K, $h = 25\,W/(m^2 \cdot K)$

温度(波导中心): 309.21 K, d = 16.06 K



所有边界: T = 293.15 K

温度(波导中心): 308.23 K, d = 15.08 K



左右下边界: T = 293.15 K

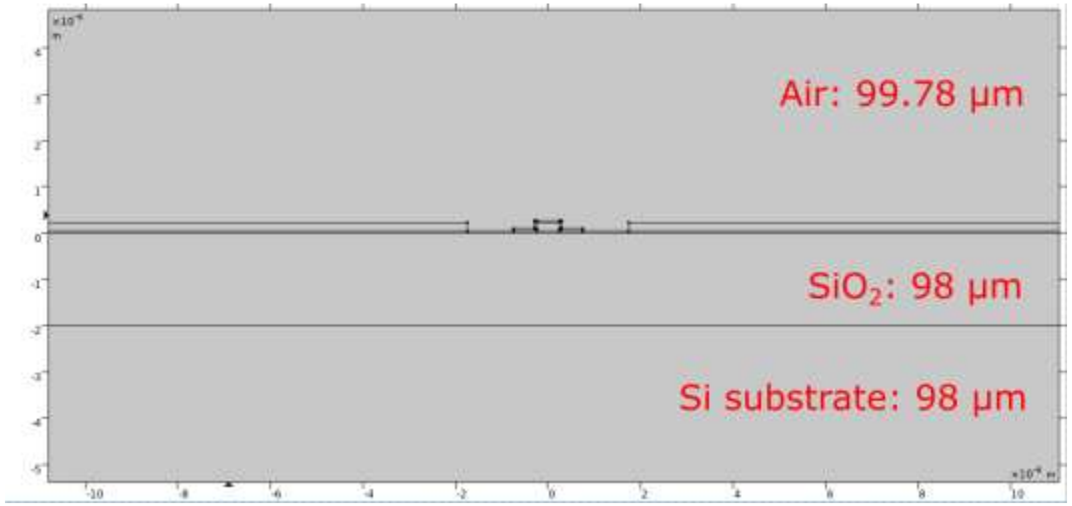
上边界: heat flux 热交换, T = 293.15 K, $h = 5\,W/(m^2 \cdot K)$

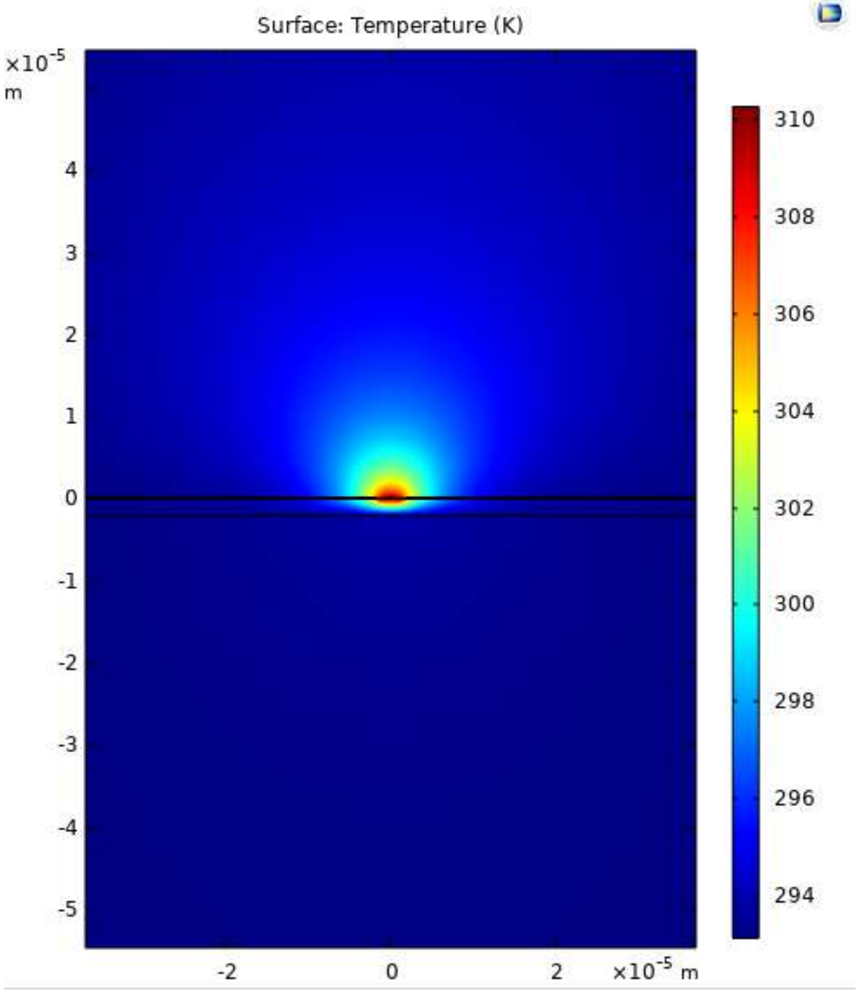
温度(波导中心): 309.21 K, d = 16.06 K

改变结构

1. 仿真区域: [μm] 100 x 200 (w, h)

2. SiO2层变为正确厚度(2 μm)

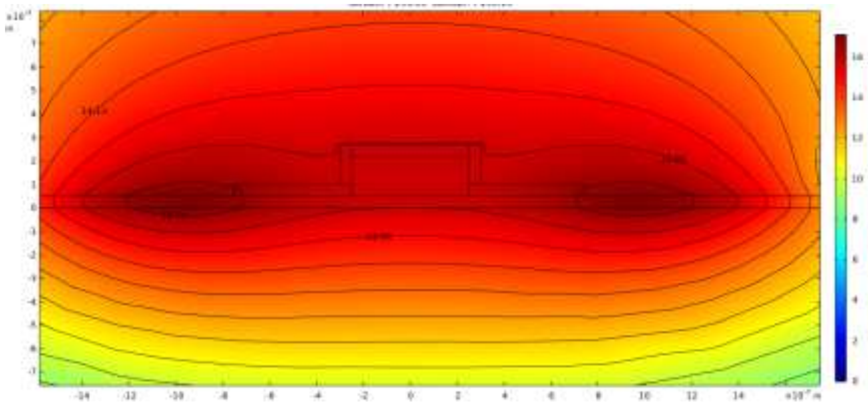




整个区域温度分布

ref

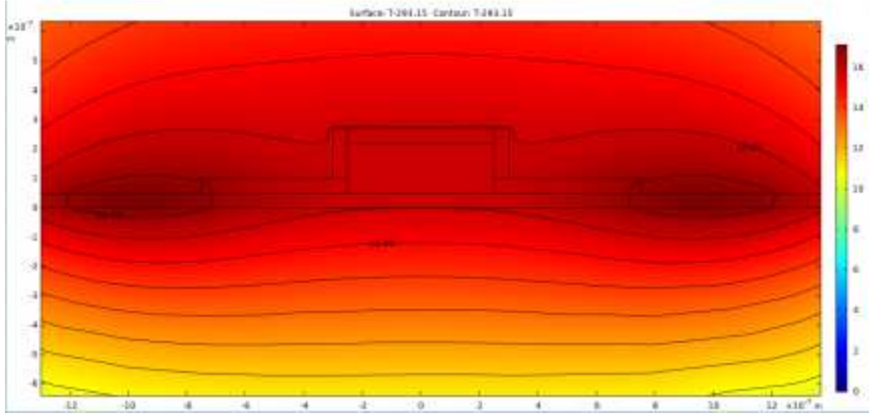
增大仿真区域



左右下边界: T = 293.15 K

上边界: heat flux 热交换, T = 293.15 K, $h = 25\,W/(m^2 \cdot K)$

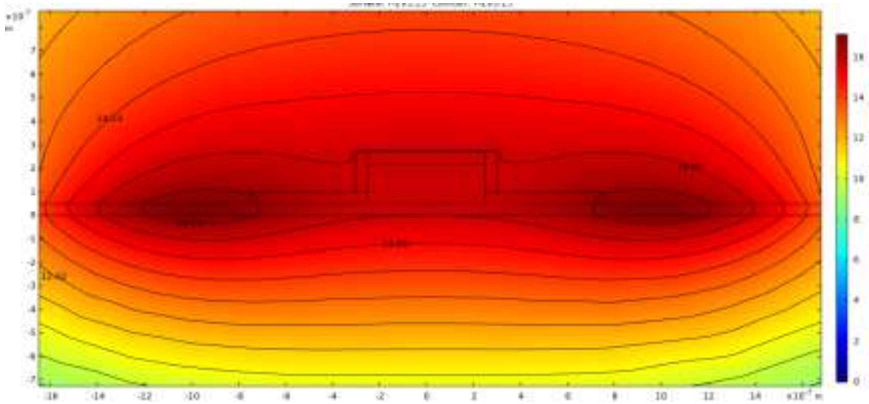
温度(波导中心): 309.01 K, d = 15.86 K



所有边界: T = 293.15 K

温度(波导中心): 309.01 K, d = 15.86 K

此时改变上边界条件基本不影响仿真结果.

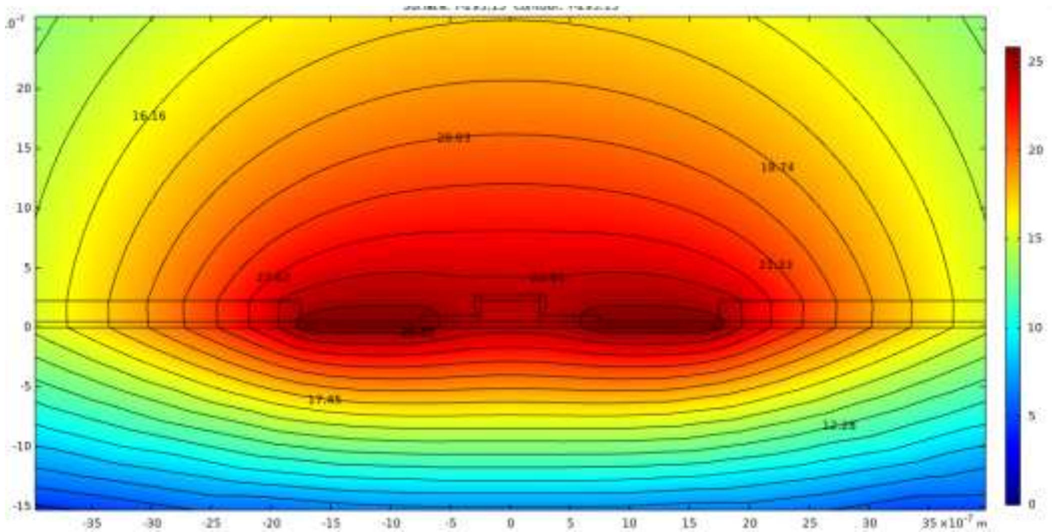


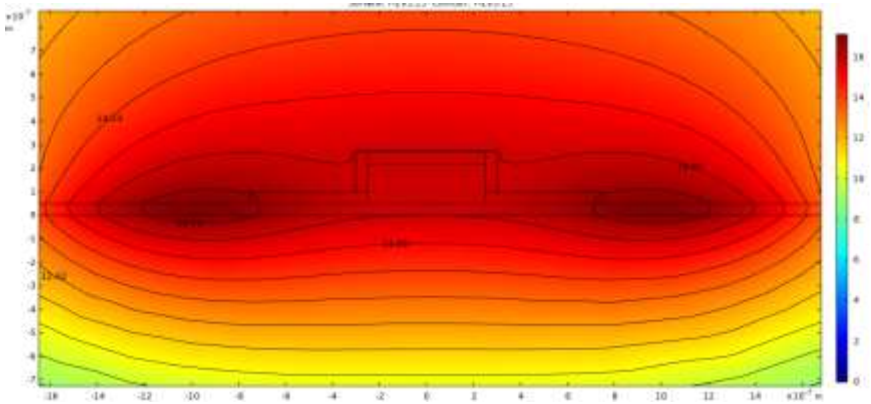
左右下边界: T = 293.15 K

上边界: heat flux 热交换, T = 293.15 K, $h = 5\,W/(m^2 \cdot K)$

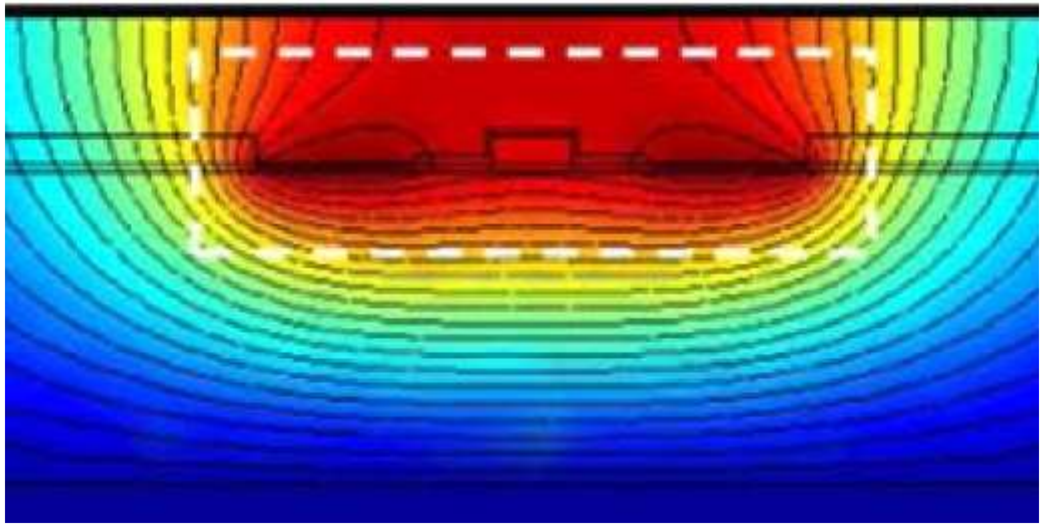
温度(波导中心): 309.01 K, d = 15.86 K

疑问

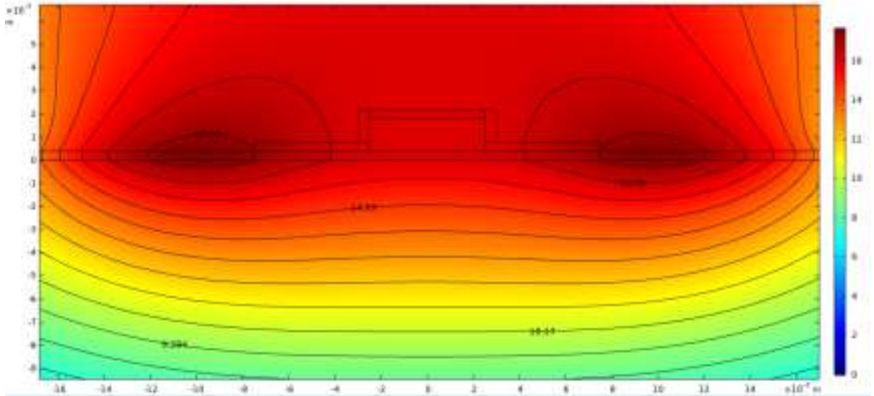




上页中等温线与论文中”大相径庭”



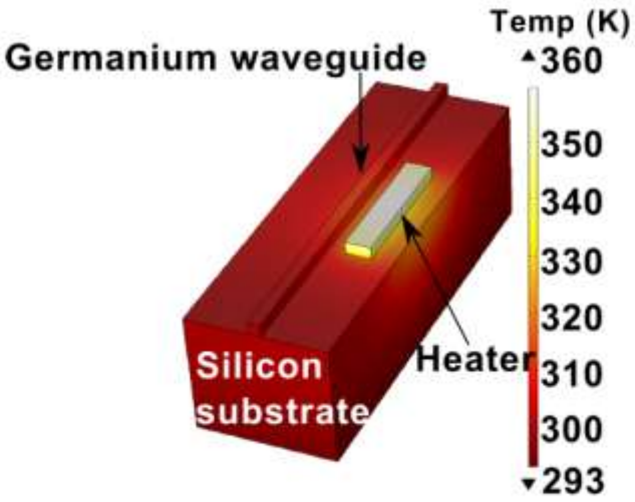
论文中等温线



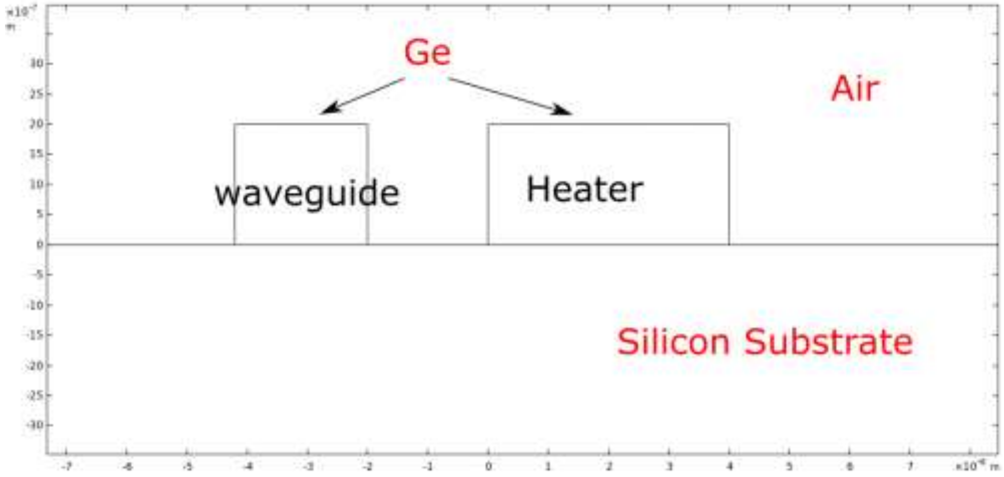
与之相似的仿真(有超链接), 条件:

厚度: 1μm, heat flux

Ref2



结构



单边加热

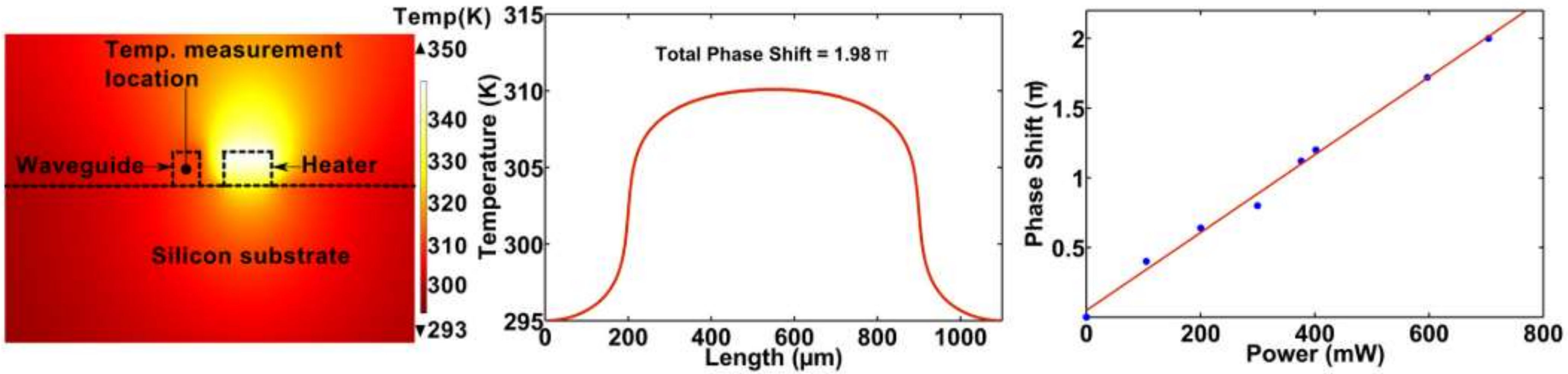
波导:[μm] 2.2 x 2 x 1100

heater: :[μm] 4 x 2 x 700

功率: 700 mW

Aditya Malik et al., Ge-on-Si and Ge-on-SOI thermo-optic phase shifters for the mid-infrared, Optics Express, 2014

论文中的仿真



(a) (b) (c)

1. 三维仿真
2. 波导中心直线上温度分布
3. 由2求得相位变化

Initial

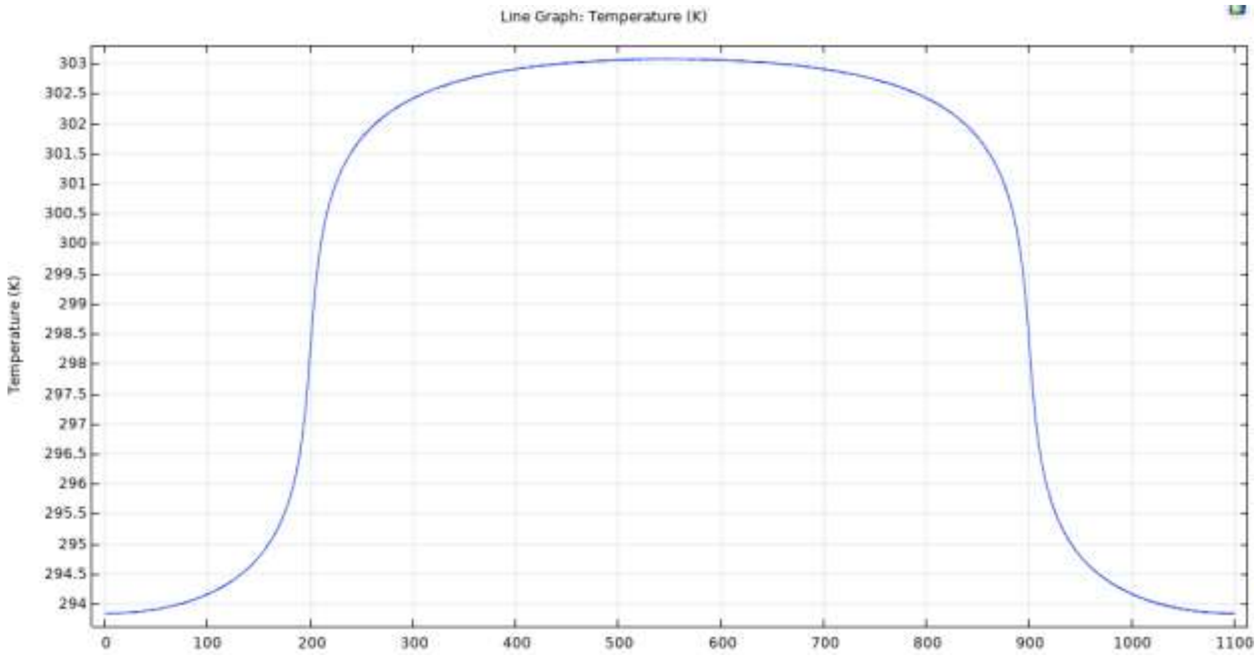
Material Property

	Thermal Conductivity (W/m*K)	Density (kg/m3)	Heat capacity (J/kg*K)
silicon	130	2330	711
air	built-in material		
germanium	58	5323	310

Boundary Condition

	Boundary Condition
上	Convective heat flux, h=10 W/(m2*K)
下	fixed temperature, T=initial value
波导方向	Convective heat flux, h=10 W/(m2*K)
其余两个方向	Convective heat flux, h=10 W/(m2*K)

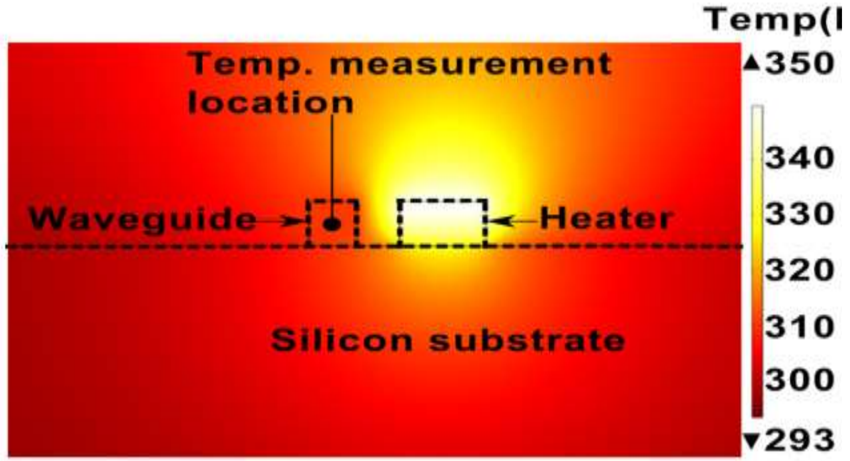
Results

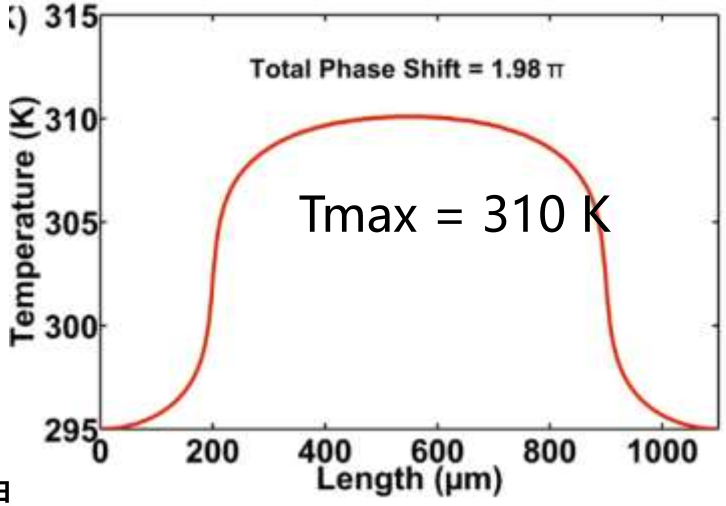


ref

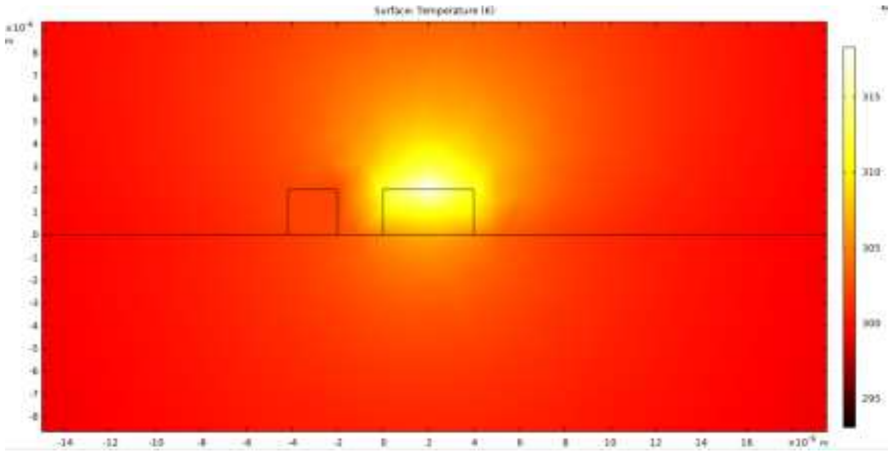
最高温度在303K左右

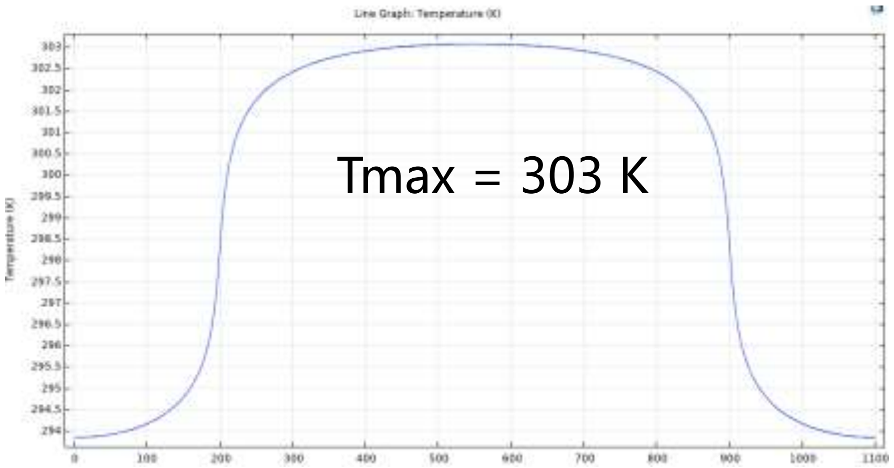
结果对比





论文结果





我的结果

左侧两图, 等温线形状不对. 且heater内部最高温度(350 K)要比我的结果(319K)高的多.

问题:

论文中结果不匹配

原因分析:

1. 可能论文中使用的是线状热源

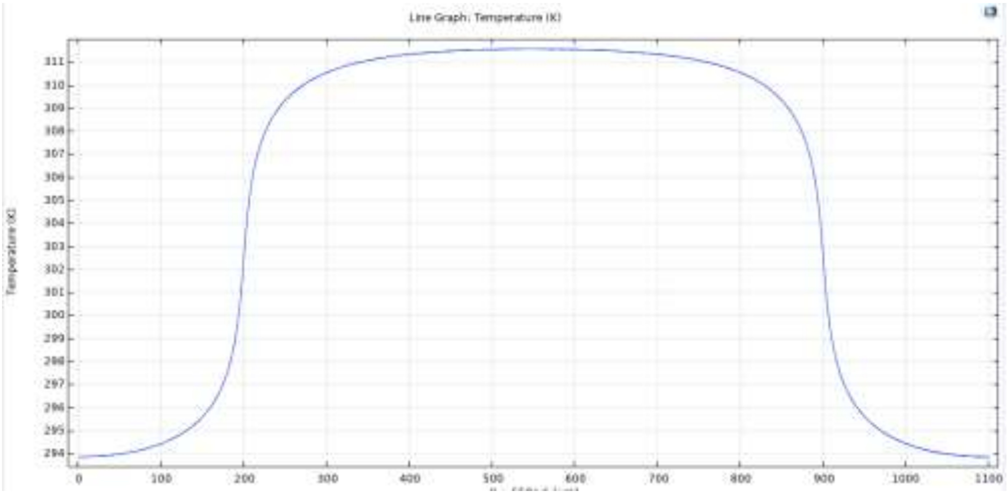
   两图等温线形状无法匹配(圆 椭圆)

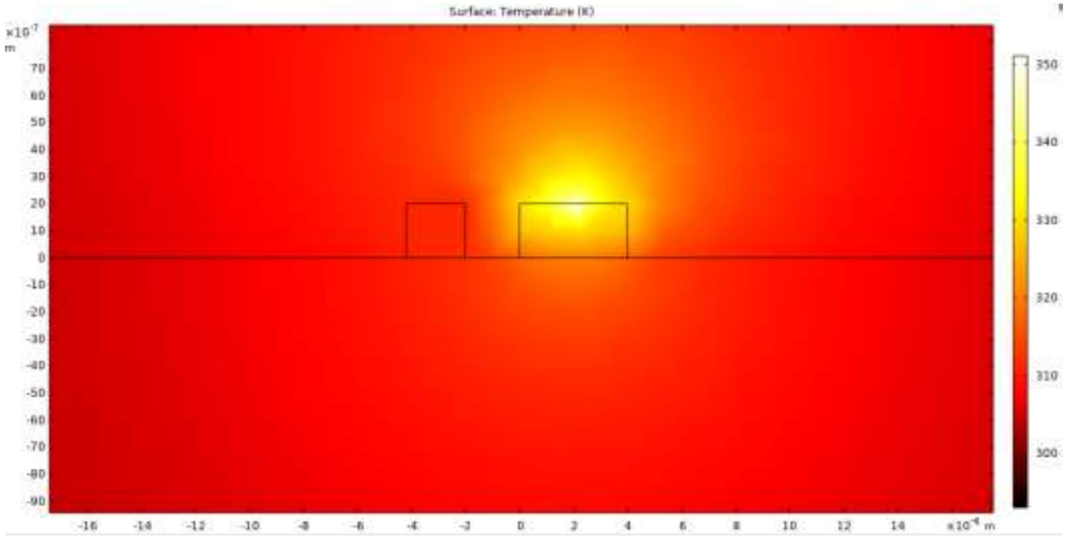
2. 边界条件错误

3. 有无可能是线段不够密集

   等温线不圆 为可见的折线段

变为线状热源





Tmax = 311.59 K

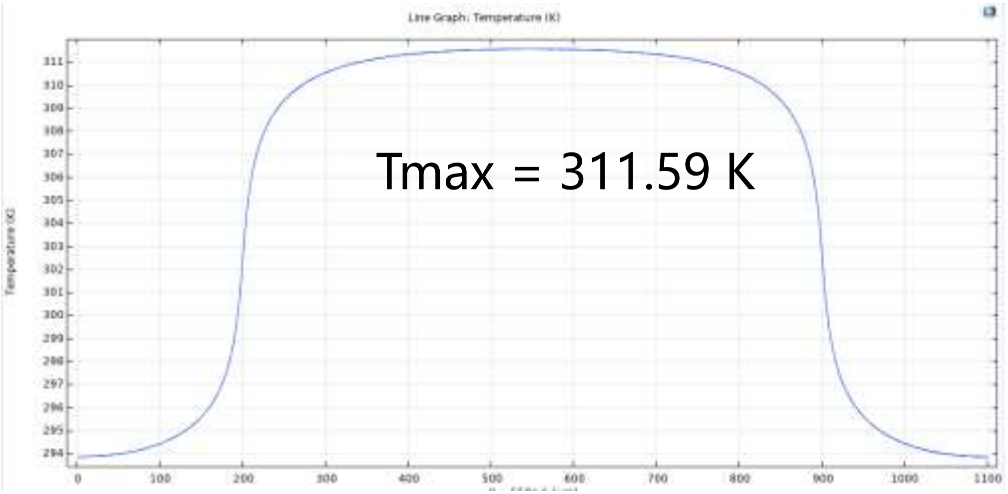
光程差 = 6.8427 = 2.178 pi

论文中:

光程差 = 1.98 pi

ref

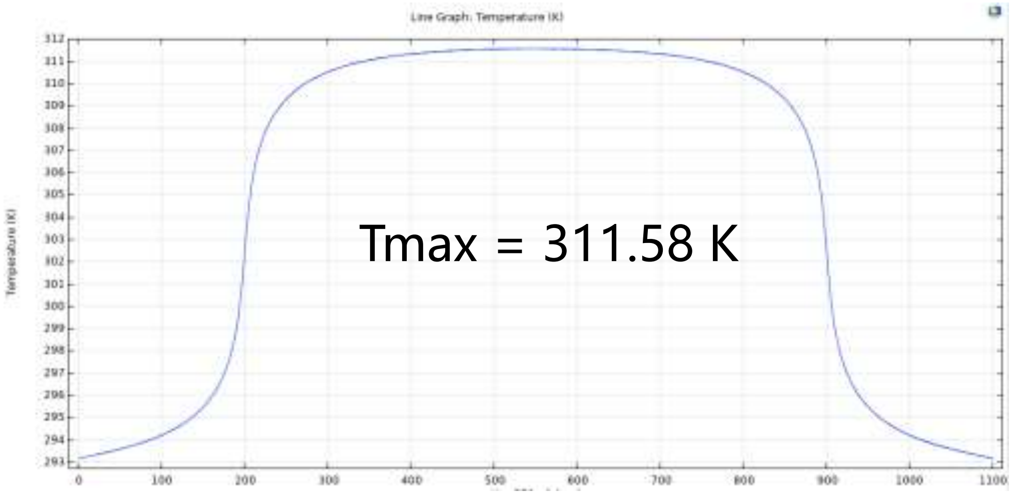
改变边界条件



上下左右边界: T = 293.15 K

波导方向边界: heat flux, T = 293.15 K, $h = 10\,W/(m^2 \cdot K)$

光程差 = 2.17 pi



所有边界: T = 293.15 K

光程差 = 2.15 pi

heat tranfer conefficients

heat transfer per unit area and per degree temperature difference

are based on:

phase of streams velocity of stream design of heat exchanger

silico dioxide thermal conductivity = 1.4 W/(m*K)

Table 3. Thermal and Electromagnetic Properties of Materials Used in FEM Simulations

Material	Thickness [μm]	Density [kg/m³]	Specific heat [J/kg·K]	Thermal conductivity [W/m·K]	Electrical conductivity [S/m]	$n_{\lambda = 1550\text{ nm}}$ -	$\kappa_{\lambda = 1550\text{ nm}}$ -
Si (bulk)	>>5	2330	711	148 [32]	4.3E-4 [28]	-	-
Si (wg)	0.22	2330	711	90 [32]	4.3E-4	3.476	0
Si (slab)	0.09	2330	711	55 [32]	4.3E-4	3.476	0
N_{++} Si[a]	0.09	2330	711	25 [29,38]	1.0E + 5 [33]	3.072 [30]	0.137 [30]
TiN	(withheld)	5240 [34]	598 [36]	28 [34]	2.3E + 6 [35]	-	-
SiO_2	(withheld)	2203	709	1.38	1E-11	1.55	0
air	>>5	1.177	1006	0.026	1E-12	-	-

[a]Highest doping dosage available.

Ref 3

Structure

area:

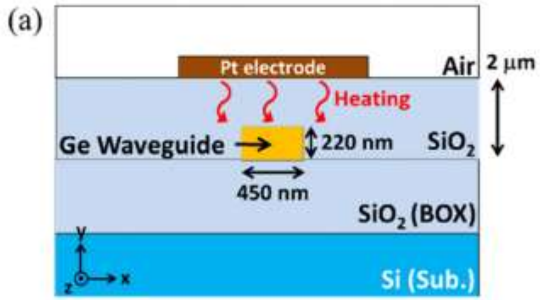


Fig. 1. Cross-sectional schematics of (a) Ge and (b) Si TO phase shifters operating at a wavelength of 1.95 µm.

Simulation

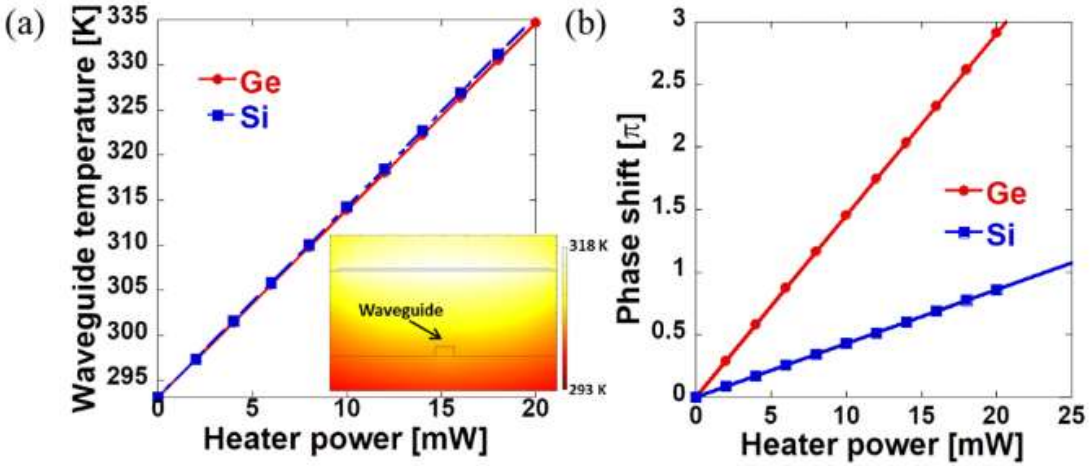
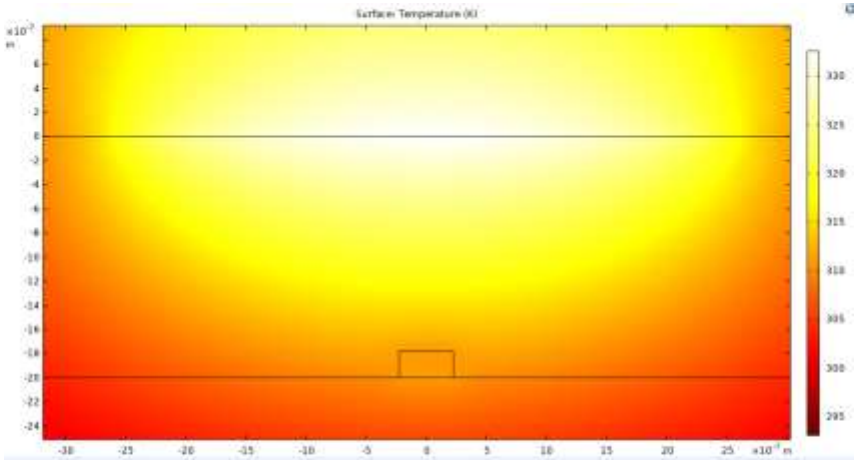


Fig. 2. Simulation results of (a) waveguide temperature and (b) phase shift in Ge and Si TO phase shifters as a function of heater power.

Takumi Fujigaki et al., High-efficiency Ge thermo-optic phase shifter on Ge-on-insulator platform, Optics Express, 2019

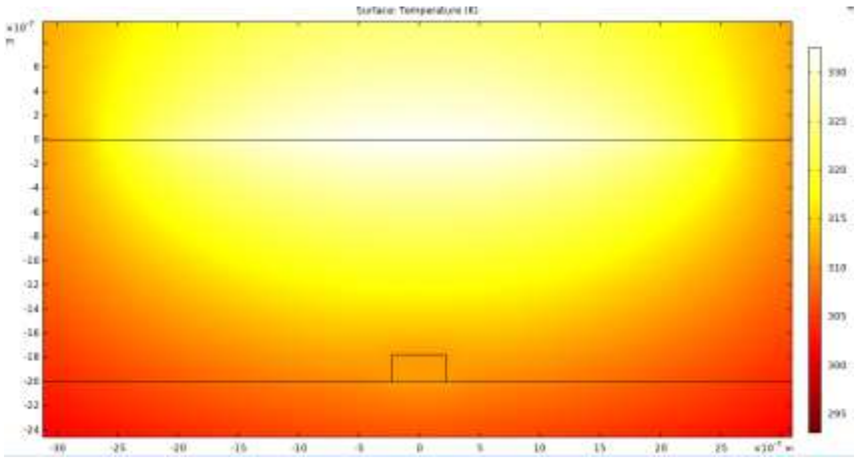


波导中心处温度: [K]

文献中: ~ 314

initial

311.11



initial-air-fluid

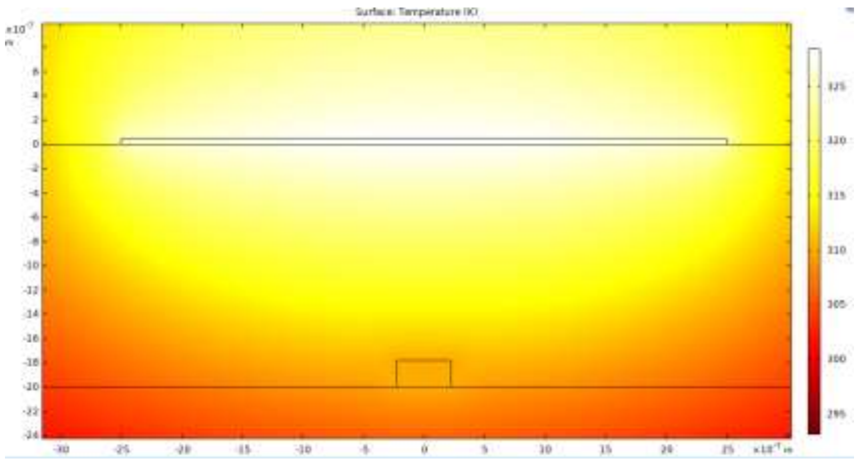
将air设置为流体

结果: 结果完全相同(exactly the same)

结论: 使用流体应设置压强 流速等

不适用与本情况

311.11



initial-pt-added

添加了薄pt层

结果: 轻微变化 (slightly different)

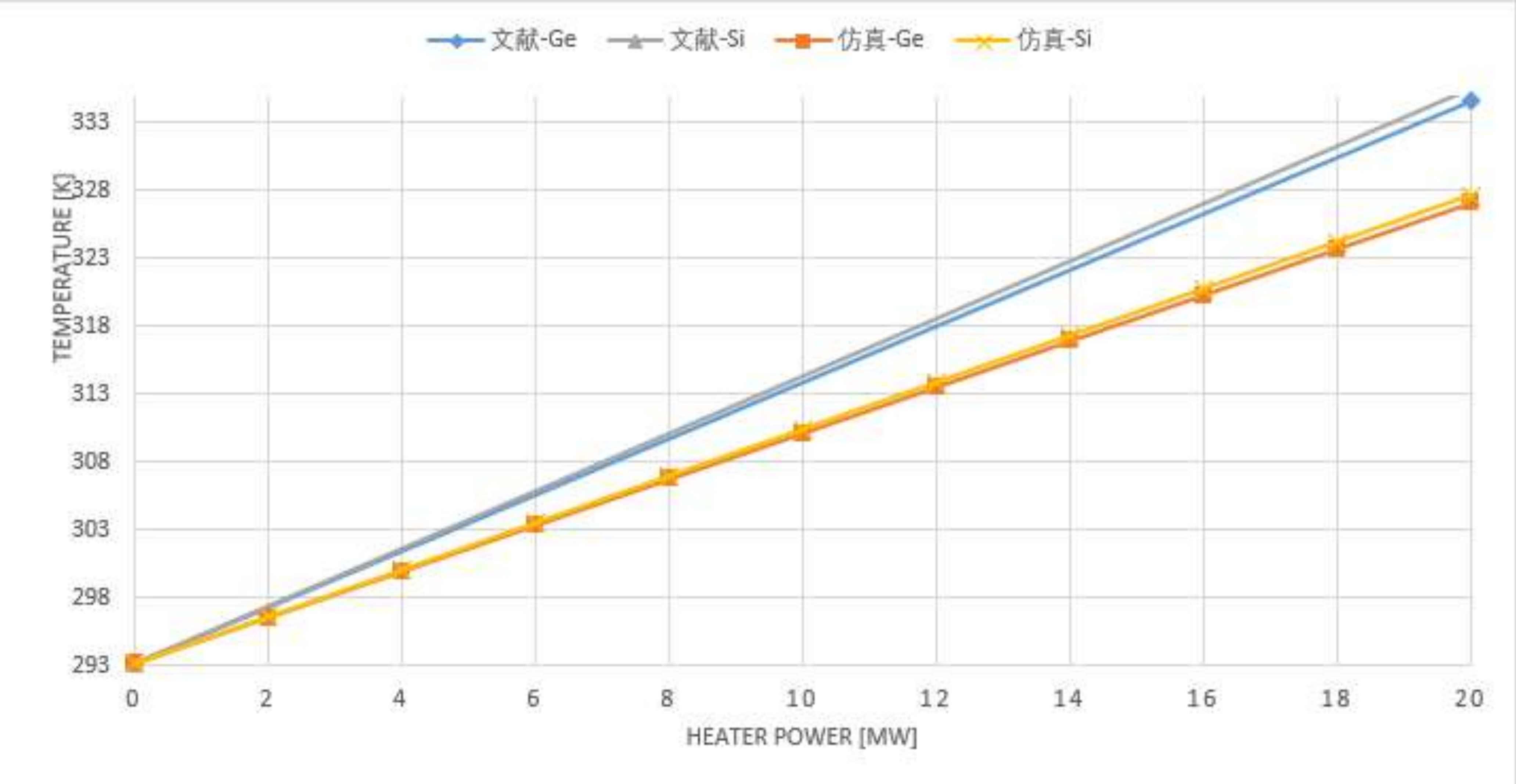
310.14

Observation:

1. steady-state 与电学联系
   1. 形成平衡需要热源(source)和热井(sink), 热井可以是边界条件确定的 – 可以类比为高电势和低电势
   2. 热的传导: 热源和各个热井之间的材料形成热阻, 类比电阻
   3. 稳态解温度分布由热阻分布决定 – 电势分布由电阻决定
2. 稳态解的分布只与物体的导热系数(thermal conductivity)有关, 而与物体的比热容(specific heat)和密度(density)无关.

-- 解释上页中添加Pt层后温度变化

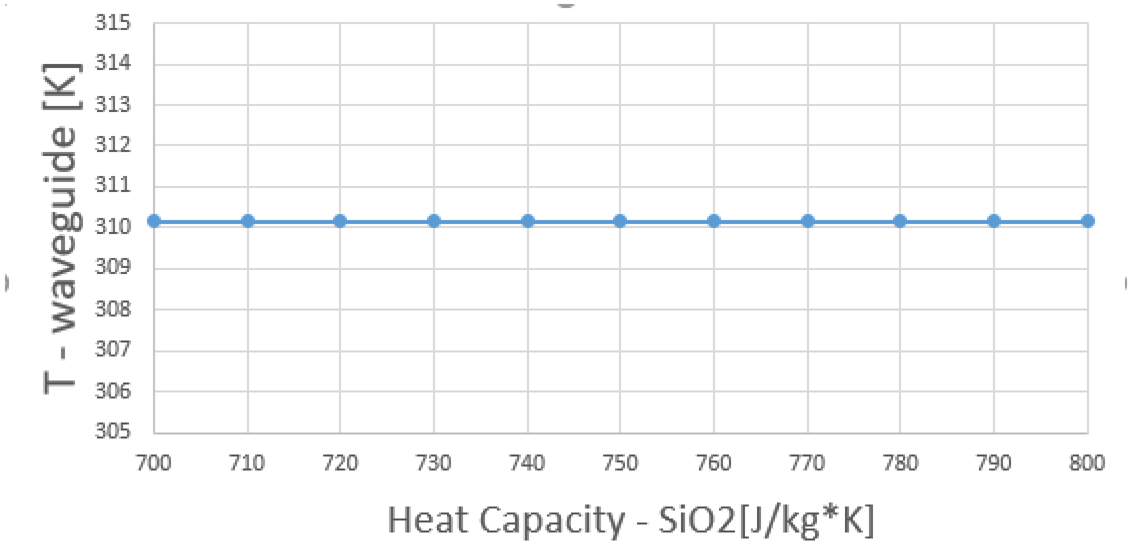
仿真结果

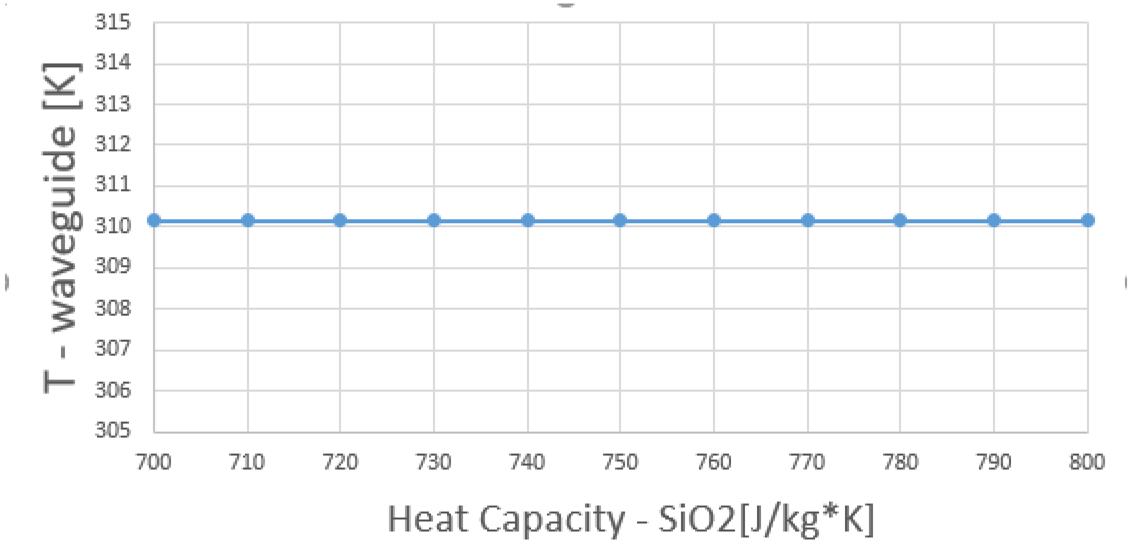


文献-Ge
文献-Si
仿真-Ge
仿真-Si
TEMPERATURE [K]
333
328
323
318
313
308
303
298
293
0
2
4
6
8
10
12
14
16
18
20
HEATER POWER [MW]

ref

验证: 材料的heat capacity, density不影响steady-state仿真结果





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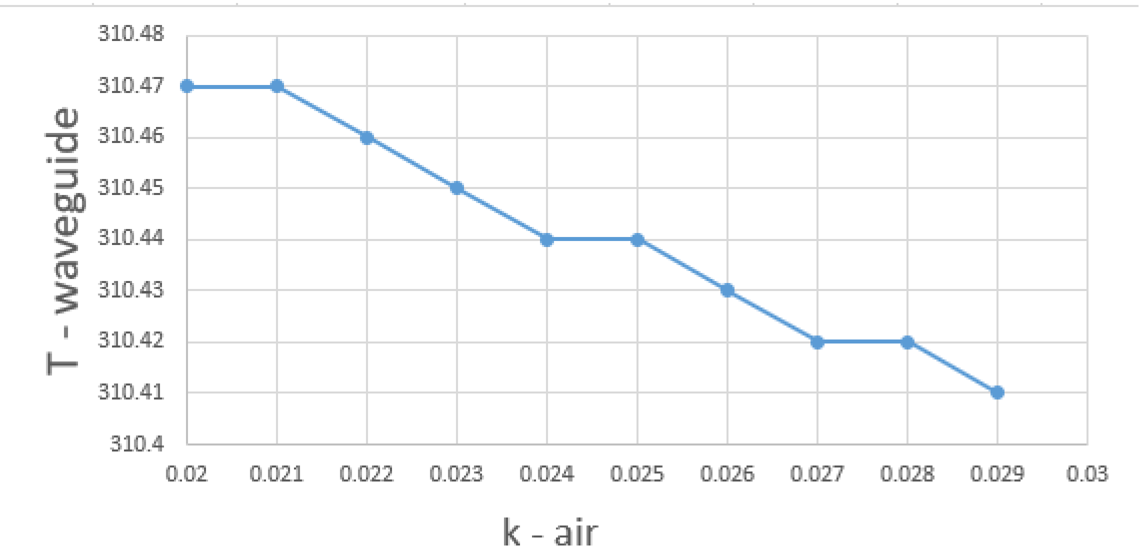
改变空气导热系数的影响

猜想: K 上升, 空气侧热阻减小, 热源产生的热更多的从空气侧流失, 下侧温度降低.



结论: 与猜想相同, 但改变幅度 < 1 K

ref