# بررسی تولید امواج THz کم اتلاف در یک موجبر پربازده معلق فلزی

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**چکیده – یک نانو منبع کوک پذیر برای تولید امواج تراهرتز(*THz*) پیوسته بر پایه تولید فرکانس تفاضلی طراحی و مشخصه یابی شده است. در این مقاله موجبر های پلاسمونیک در راستای محدود سازی نور در ابعاد نانو بهینه سازی و مشخصه یابی می‌شوند. این ساختار جدید مزایای بسیاری برای تولید امواج *THz* کارآمد تر و با بهره بسیار بیشتر ارائه می‌دهد. محاسبات انجام شده بر روی این موجبر نشان می‌دهد که بهره وری برای تولید *0.6 THz* حدود سه برابر بزرگتر از موجبر های دیگر است و همچنین اتلاف در این نوع موجبر بسیار کمتر است. در ضمن این موجبر با تغییر فاصله بین دو تیغه‌ی خود توانایی کوک پذیری سریع و آسانی را داراست.**

کلید واژه- اپتیک غیر خطی؛ اپتیک یکپارچه؛ امواج THz

# Efficient low loss nano-metallic suspended waveguide for THz waves generation

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Abstract- A tunable nanosource of continuous wave terahertz radiation based on difference frequency generation (DFG) is proposed and investigated. In this work we extend and optimize surface plasmon-polariton (SPP) waveguides to confine light to nanoscales. This new structure offers many advantages to produce more efficient THz waves with lower loss. The calculations indicate for frequency 0.6 THz efficiency is about 3 times larger ($12\times10^{-4}$ $W^{-1}$ from a 1cm long device) with lower loss. Indeed air gap distance variations to find the phase matching condition don’t affect on overlap factor.

Keywords: nonlinear optics; integrated optics; terahertz waves.

## 1 Introduction

Recently significant progresses have been made to develop efficient and coherent terahertz (THz) sources[1]. Among all techniques to generate coherent THz radiation, the difference frequency generation (DFG) process can be successfully used to develop compact, adjusted and room-temperature operated sources[2-5]. In this process two optical beams with their frequencies separated by a few THz, interact in a nonlinear medium to generate a THz beam.

A waveguide with surface plasmon-polariton (SPP) modes is capable to confine lights to nanoscales. But due to its high propagation loss, it is desired to design a plasmonic waveguide with strong field confinement and low propagation loss.

In present work, we have a novel structure to provide more efficient THz waves with lower loss in a nano-scale waveguide. We propose a nano-plasmonic suspended waveguide that optical wave is confined in a nano-scale GaAs rib waveguide and THz wave is spread out to the air gap. Air gap is the distance between quartz slabs. To calculate the phase matching and THz output power, we use finite difference time domain (FDTD) method[6] to obtain the effective index, wave number β, loss, and the modal profile of THz and optical modes. We use a computational window size of 400nm by 600nm with a minimal grid spacing of 1nm. After attaining the modal information, we obtain the THz output power and hence the conversion efficiency.

## 2 Modeling and Simulation

The structure must be designed to support both optical and THz waves, hence range choice is essential in operating the device. Several parameters should be considered and calculated to obtain the optimal waveguide geometry. First of all we consider the light confinement. In nanowires and photonic crystals the optical field confinement is limited to the order of a wavelength, so micron scale for a dielectric waveguide is an optimal scale for confining the optical wave. However, a single-mode THz dielectric waveguide is a highly multi mode for an optical wave. On the other hand some new challenges arise in dealing with light confinement in nanoscale. To overcome these problems we use surface plasmon (SP) waveguides which are able to provide light confinement in nano-scales[7].

In designing, another important parameter should be considered that affects on the efficient THz waveguide source is the phase matching between optical and THz wave. Material selection is also important since they must have low loss in both optical and THz wavelength. Geometrical dimension in fig. 1 are chosen such that phase matching condition and maximum THz power at 0.6 THz to 0.8 THz can be achieved. The tunability can be attained by varying the air gap distance.

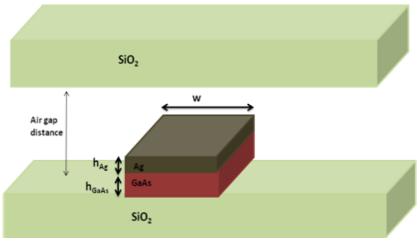


Fig. 1 two dimensional schematic of nano-plasmonic suspended integrated waveguide with a GaAs as core.

In the DFG process we assume that the two optical pump waves are polarized along the y direction, consequently the THz wave which is generated through type I phase matching has the electric field along x direction. The orientation of GaAs crystal is chosen such that [011] direction coincides with the y-axis, and [100] direction coincides with the x-axis. In this condition THz wave is generated through $d_{14}$ = 46.1 pm/V [8]. This GaAs configuration is also used in other THz conversion devices 3.

If there is no metal, optical confinement in GaAs would not occur. But the presence of metal, for larger thickness than 30nm, causes field distribution enhancement in GaAs layer 9. On the other hand, our analyses indicate that when the Ag thickness is larger than 100nm, the response of waveguide is different. In this case nano-confinement of optical wave will not occur perfectly and it mostly spreads around the metal layer and air gap. The challenge to design nano waveguides for THz generation based on DFG process is the limitation of confinement of both optical and THz wave and the very large wavelength difference between the optical and THz wave as well. Figure 2(a) shows the intensity distribution of the present waveguide, for the fundamental optical mode at pump wavelength of λ=1550nm.

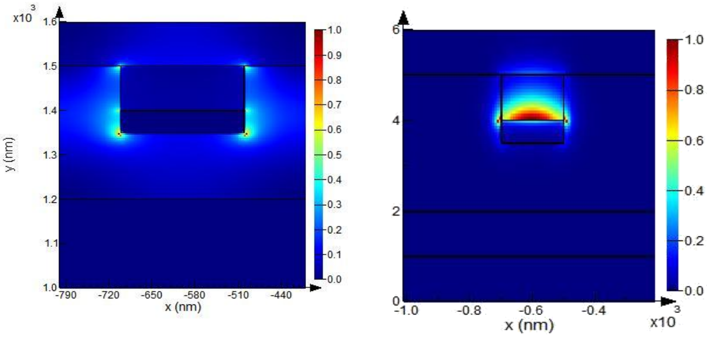


Fig. 2 (a) the real part of $E_y$ of the optical guided mode at the wavelength λ =1.5 µm. (b) real part of $E_x$ at the frequency of 0.6 THz.

In the THz frequency range, the waveguide supports a single quasi-TEM mode which propagates around the metal. Figure 2(b) shows the intensity distribution for the THz mode at 0.6THz

## 3 Results and Discussion

THz wave is confined between two $SiO_2$ waveguides. So it is expected to be significantly affected by the air gap variations. This means variation of the air gap distance is able to alter the THz effective index of the waveguide. FDTD calculations for effective index, confirm this expectation in Fig. 3.

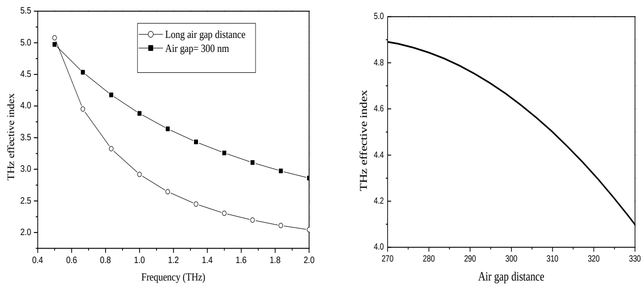


Fig. 3 (a) THz effective index as a function of THz frequency when the geometry parameters are fixed. (b) THz effective index for f = 0.6 THz guided mode as a function of the air gap.

For a long air gap distance the index of THz modes is essentially affected by the metal, GaAs and the air. This means that THz guiding mode does feel the other $SiO_2$ slab.

In principle to achieve the maximum efficiency, phase matching must be satisfied. It can be equivalently described as $n_{THz}=n_g$, where $n_{THz}=c\beta_3/\omega_3$ is phase index of the THz wave, $n_g=\dfrac{\beta_2-\beta_1}{\omega_2-\omega_1}$ is the group index of the optical waves, and c is the speed of light in vacuum.

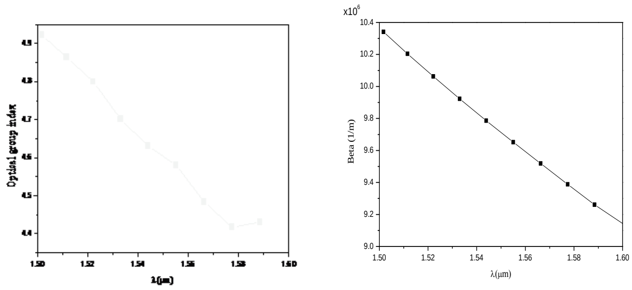


Fig. 4 (a) group index and (b) dispersion relation for optical guided modes as a function of wavelength when the geometrical parameters are fixed.

This figure makes our approach of phase matching feasible. Phase matching can be achieved at any THz frequency that $n_{THz}$ can be matched to $n_g$ of an optical wavelength. For example if we want to generate 0.6THz we have $n_{THz}$=4.64 which should be equal to $n_g$, that can be obtained at central wavelength of 1.56µm. We note that the difference frequency of two incident optical wavelength is equal to 0.6THz.

The overlap factor is defined as fraction of power for fundamental optical mode that can propagate in THz mode.

$$\text{Overlap factor} = \mathrm{Re}\left[\frac{\left(\int \overrightarrow{E_{Optical}}\times\overrightarrow{H^{*}_{THz}}.d\vec{S}\right)\left(\int \overrightarrow{E_{THz}}\times\overrightarrow{H^{*}_{Optical}}.d\vec{S}\right)}{\left(\int \overrightarrow{E_{Optical}}\times\overrightarrow{H^{*}_{Optical}}.d\vec{S}\right)}\right]\frac{1}{\mathrm{Re}\left(\int \overrightarrow{E_{THz}}\times\overrightarrow{H^{*}_{THz}}.d\vec{S}\right)}$$

Numerical calculations show that overlap factor between the optical and THz mode is 0.4031.

We change the air gap distance to find the perfect phase match condition and hence achieve the maximum THz efficiency. These variations affect on the overlap factor and consequently decrease the efficiency. But here as it is obvious in fig. 2, the overlap between the optical and THz mode doesn’t relevant to the air gap.

THz efficiency in phase matched condition for different device lengths has been plotted in fig .5.

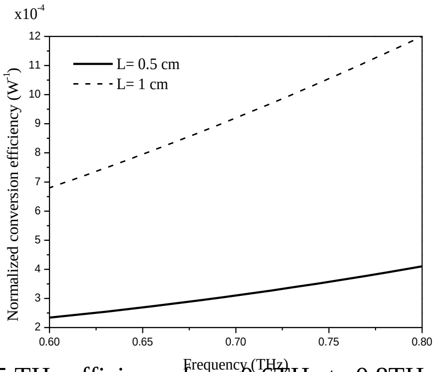

Fig. 5 THz efficiency from 0.6THz to 0.8THz for different lengths of device.

Fig. 7 shows numerical calculations of THz efficiency for 0.6 THz to 0.8 THz. The THz efficiency for the proposed suspended waveguide [5], in a 1cm long waveguide at 0.6THz is predicted to 4.26×10-4W-1. But using this configuration the efficiency is about 3 times larger, indeed air gap changes for finding the phase matching condition don't affect on overlap factor.

## Conclusion

We have extended the application of suspended waveguides to generate coherent THz wave base on DFG process. We have used SP waveguides to design a tunable and low loss source of THz waves. Numerical calculations indicate that THz efficiency is about 3 times larger than the previous suspended waveguide[5] with one order lower loss while efficiency of 1cm long device at 0.6 THz is $4.26\times10^{-4}W^{-1}$. Another advantage of this new structure is that air gap distance variations, for finding the phase matching condition, don't affect on overlap factor.

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