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SEMICONDUCTOR LASER WITH A BICONICAL WAVEGUIDE

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Abstract

The propagation losses in the fundamental mode of a bicone made of highly reflecting metal or a dielectric of large refraction were approximately estimated using Leontovich's boundary condition. A 400-fold concentration of the energy flux density has been obtained in a cross section which is much smaller than λ. Here, the losses are 2.5% at $\lambda = 550$ nm in an Ag bicone and 12% in a semiconductor bicone with a band gap of $\approx$1 eV for $h\nu$ larger than the band gap. The excitation efficiency of a bicone has been estimated. While not too large, it can be increased significantly using the method proposed in the present paper. The application of the optical bicone for the multiplication of a semiconductor-laser frequency is discussed. The results obtained are also of use in scanning near-field optical microscopy and in experiments on focusing laser pulses of ultrahigh power.

1. Introduction

Semiconductor lasers have been finding extensive application in various high-tech devices. However, it is well known that the characteristics of these devices would be noticeably improved for 2–4 times shorter lasing wavelength. Variation of the latter requires a change in the chemical composition of the compounds used in the fabrication of the semiconductor laser. This demands substantial modifications in semiconductor technology. We discuss below an alternative approach to the solution of the problem of increase in semiconductor laser frequency. This approach consists in the multiplication of the laser frequency. For efficient nonlinear frequency conversion (including multiplication), enhanced intensity of the laser radiation is needed.

In the present paper, we discuss a biconical waveguide integrated with a laser in the same crystal, which provides a multiple increase in the radiation intensity. In some sense, this device is a development of the idea of Javan's metal–oxide–metal diode [1]. Radiation with $\lambda = 3.39$ μm was obtained by frequency multiplication using such a diode.

In [2], we considered the subwavelength concentration of an electromagnetic field with a double-connected conical waveguide (bicone). Experiments on the excitation of convergent and divergent optical waves in the bicone with a vertex having a rounding radius much smaller than the wavelength were also described there. Our first results on this problem were presented in [3, 4].

Experiments on the subwavelength concentration of a microwave electromagnetic field with a so-called bow-tie antenna were described in [5]. The bow-tie antenna was fabricated from two metal triangles whose vertices were in close proximity without touching each other. The electromagnetic field is concentrated in the small area between the vertices of the triangles. It is clear that the bow-tie antenna is one version of the biconical waveguide.

To our knowledge, the problem of fabrication of a waveguide with vertices of cones several nanometers in size is solvable using state-of-the-art technology. The metallic electrodes made in the shape of triangles have been reported in [6]. The distance between the vertices of the triangles was 4 nm, with the rounding

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radius close to 10 nm. Such electrodes are well suited as a bow-tie antenna for the concentration of the laser radiation.

It is common knowledge that the results of microwave theory and experiments are not directly applicable in the optical wavelength range. The dielectric properties of metals at the optical frequencies differ substantially from those in the microwave range. The permittivity ε of the well-reflecting metals at the optical frequencies is

$$\varepsilon = -|\varepsilon'| + i\varepsilon'', \qquad |\varepsilon'| \gg 1\,, \quad \varepsilon'' \ll \varepsilon'.$$

At the microwave frequencies,

$$\varepsilon = \frac{i4\pi\sigma}{\omega}\,, \qquad \frac{4\pi\sigma}{\omega} \gg 1\,.$$

This problem calls for special investigation, which is performed below. The propagation losses in the fundamental mode of the optical bicone made of highly reflecting metal or of a dielectric of large refraction at wavelengths close to 1 μm, 550 nm, and in the hard UV range (40 and 10 nm) were found by the method of successive approximations. The excitation efficiency of a bicone was estimated.

2. Results of Calculations

Let us consider the approximate boundary condition for the tangential field components (Leontovich's boundary condition [7, 8]) at the interface of two media, one of which having $|\varepsilon_1| \cong 1$ and the other having $|\varepsilon| \gg 1$:

$$\vec{E}_t = \sqrt{\frac{\mu}{\varepsilon}}\left[\vec{H}_t, \vec{n}\right], \tag{1}$$

where $\vec{n}$ is the normal to the surface. With $\mu = 1$, $|\varepsilon| \to \infty$, and bounded $\vec{H}_t$, we have $\vec{E}_t = 0$, which coincides with the condition at the perfectly conducting boundary. Due to the equation

$$\frac{i\omega}{c}\,\vec{H} = \operatorname{rot}\vec{E}\,, \tag{2}$$

the equality $\vec{H}_n = 0$ follows from the equality $\vec{E}_t = 0$ at the surface [8]. Actually, let us perform the following calculations. We take an area S at the interface and integrate Eq. (2) over this area. After transforming the integral of $\operatorname{rot}\vec{E}$ to the contour integral, in view of the Stokes theorem, we finally obtain

$$\frac{i\omega}{c}\int\limits_S \vec{H}\cdot\vec{n}\;dS = \int\limits_S \operatorname{rot}\vec{E}\cdot\vec{n}\;dS = \oint\limits_C \vec{E}_t\cdot d\vec{l} = 0\,. \tag{3}$$

At reasonably small S, we can extract the factor $\vec{H}\cdot\vec{n}$ outside the integral sign as a constant. Hence it follows that H_n is also equal to zero in alternating fields ($\omega \neq 0$) at the surface with $\vec{E}_t = 0$.

The conditions $\vec{E}_t = 0$ and $\vec{H}_n = 0$ appear to be the same as in a boundary problem with perfect conductors, which is solved as an outer problem. Thus, it is possible to use the known solutions for

$$\varepsilon = i\varepsilon'' = \frac{i4\pi\sigma}{\omega} \gg 1$$

as a zeroth-order approximation for other values of ε, whether it be an imaginary, complex, or real negative quantity.

For Ag at $\lambda = 550$ nm, we have [9]

$$\varepsilon = -|\varepsilon'| + i\varepsilon'' = -12.7 + i\,0.46$$

Using

$$\begin{aligned} E_\theta = H_\varphi &= \frac{A}{r\sin\theta}\, e^{-i\omega r/c}, \\ E_r = E_\varphi &= H_r = H_\theta = 0\,, \end{aligned} \tag{4}$$

as a zeroth-order solution [10], one can obtain $\vec{E}_t$ from (1) and then the inward energy flux in the metal. Here, the true value of ε should be used in (1). The real part of the flux are the losses of a pure transverse (TEM) convergent wave propagating towards the vertex.

The radial component of the field near the surface of the imperfect cone inside the bicone deduced employing (10) and (4) is equal to

$$E_r = \sqrt{\frac{1}{\varepsilon}} H_\varphi = \left(\frac{\varepsilon''}{2\,|\varepsilon'|^{3/2}} - i\,|\varepsilon'|^{-1/2}\right) H_\varphi\,. \tag{5}$$

One should take for H_φ the value of the magnetic field in a zeroth-order approximation. As a result, we have

$$\mathrm{Re}\,\vec{P} = \frac{c}{4\,\pi}\,\frac{\varepsilon''}{2\,|\varepsilon'|^{3/2}}\, H_\varphi^2(\theta = \theta_1, \theta_2)\,. \tag{6}$$

The losses dN at the arc portions of cones of width dr, which are at a distance r from the vertex, are

$$dN = \frac{c}{2}\,\frac{\varepsilon''}{2\,|\varepsilon'|^{3/2}}\left[H_\varphi^2(\theta_1)\sin\theta_1 + H_\varphi^2(\theta_2)\sin\theta_2\right] r\,dr\,. \tag{7}$$

These losses should be normalized to the energy flux N through the bicone nappe at a distance r from the vertex. After that, one can determine the absorption coefficient α in the following way:

$$\begin{aligned} N &= \frac{c}{4\pi}\int \left[\vec{E}_\theta \cdot \vec{H}_\varphi\right]\,dS \\ &= \frac{c}{2}\int_{\theta_1}^{\theta_2} E_\theta H\varphi r^2 \sin\theta\,d\theta \\ &= \frac{cr^2}{2}\,\sin^2\theta_1\, H_\varphi^2(\theta_1)\,\ln\frac{\tan(\theta_2/2)}{\tan(\theta_1/2)} \end{aligned} \tag{8}$$

and

$$\alpha = \frac{1}{N}\,\frac{dN}{dr} = \frac{\varepsilon''}{2\,|\varepsilon'|^{3/2}}\left(\sin^{-1}\theta_1 + \sin^{-1}\theta_2\right)\left(\ln\frac{\tan(\theta_2/2)}{\tan(\theta_1/2)}\right)^{-1}\frac{1}{r}\,. \tag{9}$$

The variation of the total energy flux in the TEM wave as it propagates from a section of a transverse radius ρ_0 to that of radius ρ is described by the formula

$$N = N_0 e^{\beta\ln(\rho/\rho_0)}, \tag{10}$$

TABLE 1. Calculated Losses in the Tungsten Bicone at Two Different Wavelengths

λ	n	k	β	N/N_0, $\rho_0/\rho = 20$
40 nm	0.778	0.293	1	$e^{-3} = 1/20$
10 nm	0.9637	$3 \cdot 10^{-2}$	$5.2 \cdot 10^{-2}$	$e^{-0.156}$

where

$$\beta = \frac{\varepsilon''}{2\,|\varepsilon'|^{3/2}} \left(\sin^{-1}\theta_1 + \sin^{-1}\theta_2\right) \left(\ln\frac{\tan(\theta_2/2)}{\tan(\theta_1/2)}\right)^{-1}.$$

For Ag and $\theta_1 = \pi/4$, $\theta_2 = 3\pi/4$, we obtain $\beta = 8.2 \cdot 10^{-3}$. According to formula (10), the power of the convergent wave propagating from the section $\rho_0 = 1$ μm to the section $\rho = 0.05$ μm decreases by only 2.5%. When passing to the smaller sections, the conditions of validity of formula (1) [8] are violated. This is due to the variation of the surface curvature in such a way that the normal derivatives of the field components inside the metal are no longer greater than the derivatives in the tangential directions. The curved surface has a pronounced focusing effect on the transmitted wave.

Let us carry out a calculation for a semiconductor with an energy band gap of $\approx$1 eV. We suppose that

$$\varepsilon' = 10\,, \qquad \varepsilon'' = \frac{\alpha\lambda}{2\pi} = 1.5\,, \qquad \lambda = 10^{-4}\ \text{cm}\,, \qquad \alpha = 10^5\ \text{cm}^{-1}.$$

The chosen values are typical for Si, Ge, and GaAs. For a cone of the same geometrical shape and sections which differ by a factor of 20 (1 μm and 50 nm), one obtains an attenuation of 12%.

Let us calculate the losses in the tungsten bicone at wavelengths of 40 and 10 nm using the data on the optical constants of tungsten [11]. These data are presented in the form of the real (n) and imaginary (k) parts of the refractive index. We calculate the permittivity by the formula

$$\varepsilon = (n + ik)^2 = n^2 - k^2 + 2\,ink = \varepsilon' + i\varepsilon''.$$

The results of the calculations are summarized in Table 1:

To justify the calculations performed, we appeal to the results of [12]. It has been shown there that the fundamental, i.e., TEM wave, along a metal cylinder always exists since the conductivity of the metal σ is not strictly zero. There is a reason to think that a similar situation also happens for a tungsten cone at wavelengths of 40 and 10 nm. We shall additionally study this problem in the future.

Let us present some considerations on choosing the opening angles of the cones of a bicone. At $\theta_1 = \pi/4$ and $\theta_2 = 3\pi/4$, the height of each cone is equal to the radius of the cone base. Therefore, the part of the cone that has a small diameter is not extended. The ohmic losses in such a cone are smaller than that in a bicone made of thin long needles. A bicone composed of blunt needles has a wave impedance Z_0 of the order of 100 Ohms. In this context, the term "blunt" does not refer to the value of the rounding radius of the vertex of the cone. This radius can be as small as desired even for a blunt needle. Such a configuration is convenient in applications. A bicone composed of the sharp needles has a wave impedance of several hundred Ohms, which is less convenient. And finally, the heat flux from the tip of a blunt needle is more efficient than that from the tip of a sharp needle. This circumstance may appear to be crucial in experiments on the generation of high power densities.

We pass on now to the issue of the efficiency of excitation of a biconical light guide. One has to calculate which portion of a wave incident on the bicone is transformed into a convergent wave of the bicone. The known results of the scattering theory of a plane electromagnetic wave by a sphere (Mie theory) are used in the following calculation. The results of this theory are adopted from [12].

An incident wave induces an oscillating current in a conducting sphere. One can imagine a transverse (with respect to the induced current) section of the sphere which is shut by the bias current. In this case, a volume arises where the amplitude of the electric field is high. This volume, filled with a nonlinear substance, serves as a source of radiation with converted frequency.

The surfaces that bound this section should be made conical. The vertices of the cones are closely spaced with respect to each other without contact. When the vertexes of the cones are in contact, the magnetic field is expected to be strong. This case is favorable for the magnetic interactions.

The current amplitude is determined by the theorem on the circulation of the magnetic field

$$\oint_C \vec{H} \cdot d\vec{l} = \frac{4\pi}{c} J . \tag{11}$$

The problem is to determine the magnetic field. The magnetic field of the wave scattered by the sphere looks like

$$\vec{H}^{(s)} = -E_0 e^{-i\omega t} \sum_{n=1}^{\infty} i^n \frac{2n+1}{n\,(n+1)} \left[b_n^{(s)} \vec{m}_{e1n}^{(3)} + i a_n^{(s)} \vec{n}_{o1n}^{(3)} \right] . \tag{12}$$

Here, E_0 and ω are the amplitude and frequency of the field oscillations in the incident plane wave

$$\vec{E}^{(i)} = \vec{a}_x E_0 \, e^{ik_z z - i\omega t} ,$$

respectively. The sum in (12) contains all eigenmodes of a sphere, the coefficients $b_n^{(s)}$ being the electrical multipoles and $a_n^{(s)}$ being the magnetic ones. Further on we shall restrict our consideration to the single term with a coefficient $b_1^{(s)}$, i.e., to the electrical dipole.

The zeroth-order term is absent in the sum of (12) since the sphere does not support such a type of oscillation. However, there is good reason to assume that the results obtained below will also be applicable to a bicone.

Under these conditions, the magnetic field of the scattered wave is

$$\vec{H}^{(s)} = -E_0 \, e^{-i\omega t} \, i \, \frac{3}{2} \, b_1^{(s)} \vec{m}_{o11}^{(3)} , \tag{13}$$

where

$$\vec{m}_{e11}^{(3)} = \vec{i}_\theta \, \frac{1}{\sin\theta} \, h_1^{(1)}(kR) \; P_1^1(\cos\theta) \sin\varphi - \vec{i}_\varphi h_1^{(1)}(kR) \, \frac{\partial P_1^1}{\partial\theta} \cos\varphi , \tag{14}$$

$$h_1^{(1)}(x) = \sqrt{\frac{\pi}{2x}} \, H_{1\frac{1}{2}}^{(1)}(x)$$

is the spherical Hankel function, $H_{1\frac{1}{2}}^{(1)}(x)$ is a first-order Hankel function of half-integer index, and $P_1^1(\cos\theta)$ is the associated Legendre polynomial. The selection of the coordinate system is noteworthy. The z axis is directed along the propagation vector $\vec{k}$ of the incident plane wave, the x axis with the unit vector $\vec{a}_x$ is aligned with $\vec{E}^{(i)}$, the polar angle θ is measured from the z axis, and the azimuthal angle φ corresponds to rotation around the z axis and is measured from the x axis. The induced oscillating current $\vec{J}$ is aimed along the x axis. The circulation of the magnetic field is calculated along a contour at the surface of a sphere on the plane $\theta = \pi/2$, i.e., on the plane $z = 0$. This corresponds to the θ-component of the magnetic field, i.e., to the coefficient of $\vec{i}_\theta$ in formula (14) for $\vec{m}^{(3)}_{e11}$. The factor $\sin\theta$ included in $\vec{m}^{(3)}_{e11}|_{\theta=\pi/2}$ takes the values

$$\sin(\pi/2) = 1 \qquad \text{and} \qquad \sin(3\pi/2) = -1\,.$$

The radius of the sphere R_a will be considered close to

$$\lambda = \frac{2\pi c}{\omega}\,.$$

With such a choice of R_a, the argument of the function $h_1^{(1)}(x)$ is distinctly larger than unity. Because of this, the asymptotic formula

$$h_1^{(1)}(x) \cong x^{-1} e^{ix}$$

is found to be suitable for $h_1^{(1)}(x)$. The associated Legendre polynomial is obtained with the generating formula

$$P_n^m = \frac{(1-\eta^2)^{m/2}}{2^n n!}\,\frac{d^{n+m}(\eta^2-1)^n}{d\eta^{n+m}}\,. \tag{15}$$

Using formula (15) we obtain

$$P_1^1(\cos\theta) = \sin\theta\,.$$

The coefficient $b_1^{(s)}$ at $|kR_a| \gg 1$ has the form

$$b_1^{(s)} \cong -e^{-i\rho}\cos\rho\,\frac{\tan(N\rho) - N\tan\rho}{\tan(N\rho) + iN}\,, \tag{16}$$

where

$$\rho = kR_a\,, \qquad N = \frac{k_1}{k}\,.$$

In deriving the formula for $b_1^{(s)}$ we took into account that

$$\mu_1 = \mu_2 = \mu = 1\,.$$

It is interesting to note (vis-á-vis [12]) that the expansion coefficients $a_n^{(s)}$ and $b_n^{(s)}$ are the oscillating functions of ρ and n, which is clear also from the example of the $b_1^{(s)}$ coefficient. The swing of the oscillations is from unity to zero.

The calculated amplitude of the oscillating current is expressed as follows:

$$J_0 = \frac{3}{4}\,i\,\frac{c}{k}\,E_0\cos\rho\,\frac{\tan(N\rho) - N\tan\rho}{\tan(N\rho) + iN}\,. \tag{17}$$

For highly reflecting metal at the optical frequencies,

$$\varepsilon = -|\varepsilon'| + i\varepsilon''\,, \qquad |\varepsilon'| \gg |\varepsilon''|\,.$$

Let us assume that

$$\varepsilon \cong -|\varepsilon'|\,.$$

As a result, we have for the calculated amplitude of the oscillating current

$$J_0 = \frac{3}{4}\,i\,\frac{c}{k}E_0\,\frac{1 - i\,|\varepsilon'|^{1/2}}{1 + |\varepsilon'|}\cos\rho\,(1 - |\varepsilon'|^{1/2}\tan\rho) \tag{18}$$

for

$$N = i|\varepsilon'|^{1/2}, \qquad \rho = R_a \frac{\omega}{c}\,.$$

The function

$$\cos\rho\,(1 - |\varepsilon'|^{1/2}\tan\rho) \qquad \text{for} \qquad |\varepsilon'|^{1/2} \gg 1$$

(which is almost valid for Ag) has maxima at

$$\rho_n = 2\pi n + (3\pi/2) + \Delta\rho \qquad \text{with} \qquad \Delta\rho = |\varepsilon'|^{-1/2}.$$

After expanding $\cos\rho_n$ and $\tan\rho_n$ near $\rho = \rho_n$ into a power series of $\Delta\rho$ and keeping first-order terms, one obtains

$$J_0 = \frac{3}{4}\frac{c}{k}E_0\left(|\varepsilon'|^{1/2} + i\right)\frac{|\varepsilon'|^{1/2}}{|\varepsilon'| + 1}\,. \tag{19}$$

The absolute value of the current is

$$|J_0| = \frac{3}{4}\frac{c}{k}E_0\frac{|\varepsilon'|^{1/2}}{(|\varepsilon'| + 1)^{1/2}}\,, \tag{20}$$

and the amplitude of the oscillating charge

$$q = q_0 e^{-i\omega t}$$

reads

$$q_0 = \frac{3c}{4k\omega}E_0\,.$$

For the electric field strength in the gap we have the value

$$E = \frac{q_0}{s} = \frac{3}{4}\frac{c}{k\omega}E_0\frac{1}{a^2} = \frac{3}{4}\frac{E_0}{(2\pi)^2}\left(\frac{\lambda}{a}\right)^2, \tag{21}$$

where a is the lateral size of the vertex of the bicone.

For $\lambda = 1000$ nm and $a = 50$ nm, we have an 8-fold field enhancement in the bicone as compared to the field of the incident wave and a 64-fold increase in the power flow. Unfortunately, the numerical coefficient in the formula for E is rather small:

$$\frac{3}{4}(2\pi)^2 \cong 2 \cdot 10^{-2}.$$

The intensity of radiation impinging on the bicone should be enhanced by a Fabry–Perot interferometer with spherical mirror which is tuned to the resonance. This is commonly done in microwave experiments.

3. Discussion

Figure 1 shows a schematic diagram in three projections of a semiconductor laser with an integrated (in the same crystal) biconical waveguide and matching interferometer. This bicone has the form of a bow tie in the figure. It is appropriate to use triangular tabs having variable thickness so as to provide fixed wave impedance of the bicone along the whole length. The biconical waveguide is separated from the output facet of the laser by a gap filled with a transparent medium. This gap forms an interferometer, which provides a drastic increase in the intensity of the radiation impinging on the bicone when properly tuned. It is conceivable to fabricate the frontal surfaces of this gap as spheres. In this case, the wave impinging on the bicone becomes spherical also. This provides an additional increase in the efficiency of excitation of the

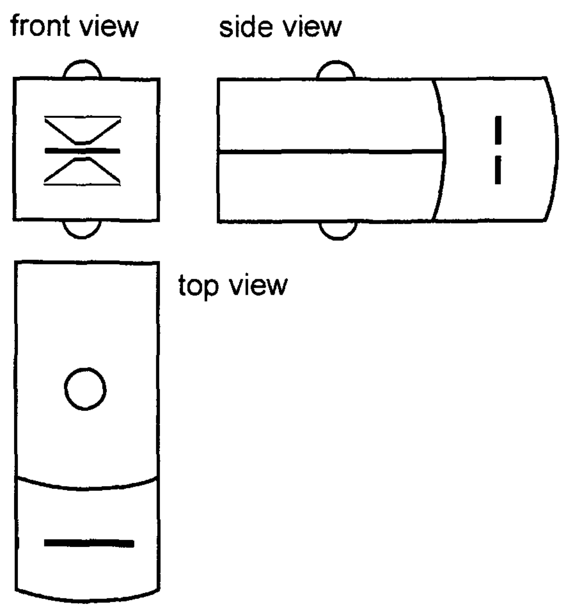

Fig. 1. Schematic diagram of a semiconductor laser with an integrated biconical waveguide in three projections.

bicone. The heights of the triangles should be a multiple of $\lambda/4$ to make it possible to have a resonance in the bicone. The conversion of the radiation frequency occurs in the nonlinear substance placed in the space between the vertices of the triangles.

Several groups have presented results of successful experiments on the excitation of the fundamental wave of the biconical waveguide (though without a discussion of the conditions of its existence) in the near infrared and optical ranges. The convergent wave traveling to the vertex of a bicone has been discussed in [1, 13, 14] whereas a divergent wave has been discussed in [15].

The field-concentration effect has been discussed in [13, 14] in terms of the electrostatic theory of dielectrics and metals. In [2] both convergent and divergent waves have been observed and discussed in terms of the waveguide theory. Experiments in the far ultraviolet range await performance, being of great importance.

4. Conclusions

To summarize, using the approximate boundary condition (Leontovich's boundary condition) the existence of the fundamental optical mode in a bicone made of highly reflecting metal or a dielectric of large refraction has been demonstrated. The mode losses for a 400-fold concentration of the power flow in a cross-section with a diameter much smaller that the wavelength have been estimated. These losses are 2.5% for a silver bicone at a wavelength of 550 nm and 12% for a bicone fabricated from a semiconductor with a band gap of 1 eV provided the energy quantum exceeds slightly the energy-band gap. The excitation efficiency of the bicone has been estimated. This efficiency is not large. Ways to increase it substantially have been proposed. The application of the optical bicone for multiplication of the semiconductor-laser frequency has been considered. The results obtained are also of use in scanning near-field microscopy and in experiments on the focusing of laser pulses of ultrahigh power. Undoubtedly, in the latter experiments the bicone will be destroyed but will produce a short-term (for a few femtoseconds) increase in the radiation intensity of any laser having a good quality spectrum.

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