WAVEGUIDE THz FEL OSCILLATORS*

Sergey Miginsky#, Nikolay Vinokurov, KAERI, Daejon, Korea; Budker INP, Novosibirsk, Russia
Sangyoon Bae, Boris Gudkov, Kyu Ha Jang, Young Uk Jeong, Hyun Woo Kim, Kitae Lee, Jungho Mun, Seong Hee Park, Gyu Il Shim, KAERI, Daejon, Korea

Abstract

In today's world there is a significant demand for FEL-based THz radiation sources. They have a wide tuning range, a narrow band of radiation, and comparably high peak and average emission power. There are a significant number of these machines in the world, operating or in the development.

The main difference between a long-wave FEL, of THz or a millimeter band, and a conventional one is a too big transverse size of the fundamental mode of an open optical resonator. It claims a large gap in an undulator that dramatically decreases its strength. Both factors sorely decrease the amplification and the efficiency, and often make lasing impossible.

The main way to solve this problem is to use a waveguide optical resonator. It decreases and controls the transverse size of the fundamental mode. However, the waveguide causes a number of problems: power absorption in its walls; higher modes generation by inhomogeneities, as it is not ideal; electron beam injection into a FEL is more sophisticated; also outcoupling is more complicated; finally, the resonator detuning control claims some special solutions. The waveguide dispersion relation differs from one in the free space. It shifts up the wavelength of the FEL, changes the optimal detuning, and creates a parasitic mode near the critical wavelength of the waveguide. These problems and possible solutions to them are considered.

INTRODUCTION

Outstanding parameters of THz FELs, like a wide tuning range, a narrow band of radiation, and comparably high peak and average emission power cause a significant number of these machines in the world. Several examples one can find in [1–7]. These machines differ significantly from each other and are intended for different purposes. One can easily found that FELs provide incomparably higher power than oscillators of other types in THz region [8].

However, there are several significant problems in development of THz FELs. Most one is that the fundamental mode of an open optical resonator has too big size in this case. It causes a decrease of the gain directly by weakening interaction between a wave and electrons and indirectly by an increase in an undulator gap that causes a sharp decline in strength of the latter. Thereby, extremely high peak current is necessary to obtain lasing. An effective method to improve the situation is the use of a waveguide optical resonator instead of open one. In this case the size of its mode can be significantly reduced together with an undulator gap. Wherein, a number of other problems arise. Energy absorption in the waveguide walls reduces the loop gain. Higher modes generation on waveguide inhomogeneities produces a similar effect. Beam injection into this resonator can be a complicated problem. Light outcoupling can be also not so easy. The wave group velocity in a waveguide depends on the wavelength, so the resonator should be retuned for each wavelength to keep the detuning. It is another sophisticated problem. Conducting of a beam through a narrow waveguide is not easy problem too. All these problems should be solved for a waveguide FEL.

WAVEGUIDE RESONATORS

Several types of waveguides shown in Fig. 1 can be used in FELs. Electric field in all the cases is horizontal. Each of them has some advantages and drawbacks.

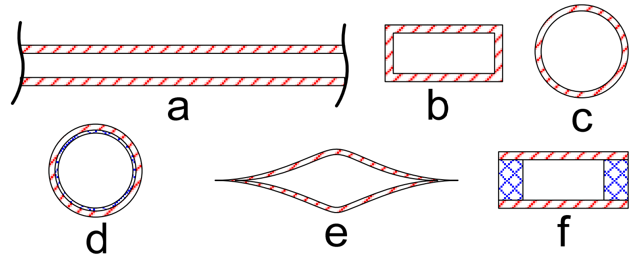

Figure 1: Types of waveguides: a – parallel-plate, b – rectangular, c – circular, d – with dielectric coating, e – special shape, f – rectangular with dielectric walls.

A parallel-plate waveguide concentrates wave power along the vertical coordinate only, while along the horizontal one it is similar to empty space. Thus, in the vertical plane the electric field distribution is cosine-like with zeroes at the walls, and in the horizontal one it is the well-known Gaussian free-space mode. It can be placed in a planar undulator only. One can conclude that the most effect of this waveguide is the decrease of the undulator gap. Power loss in this waveguide typically is not so big and can be easily evaluated using the following formula

$$\alpha \cong \frac{\pi}{2l} \frac{1}{1+\frac{i\zeta}{kl}}, \qquad (1)$$

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#Miginsky@gmail.com

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where l is the waveguide half-height, k is the wavenumber, and $\zeta = Z_s / Z_0$, the ratio of the surface impedance to the one of free space [9].

A rectangular waveguide provides much smaller fundamental mode size, thus much bigger primary gain. In the other hand, wave losses in it are very high, so the system should be optimized well and, even in this case can be unable to work. A special shape (like Fig. 1e) can be applied to reduce losses.

Also dielectric walls of a rectangular waveguide (like Fig. 1f) give similar and even stronger effect. Nevertheless, this waveguide has many drawbacks. It is very hard to manufacture such a structure, as it should be extremely uniform and vacuum-tight simultaneously. The dielectric is to be refractory and slightly conductive, so its choice is not obvious. The latter property is necessary to discharge of the current absorbed from the beam halo.

A circular waveguide is useful together with a helical undulator. In this case the gain is twice bigger than with a planar one, other things being equal. The properties of this waveguide are similar to ones of a rectangular one.

The inner surface of a circular waveguide can be coated by a dielectric to dramatically reduce power absorption. In this case the fundamental mode being used for lasing is not H_{11} as in a pure-metal waveguide, but hybrid HE_{11} one [10]. Also change in the wave structure intensifies the beam-to-light interaction. The results for an aluminium pipe of the inner diameter of 4.8 mm are placed in Fig. 2. Optimal thickness coating of low-density polyethylene (LDPE, 45 μm) or corundum (20 μm) was used. λ is the wavelength, E is the electric field of the wave, P is its power, k" is the imaginary part of the wavenumber, and Z_0 is the impedance of free space. The data were obtained from numerical simulations. The plot shows that an optimally coated circular waveguide is up to 70 times more effective than pure-metal one. The kind of polymer almost does not matter, so technological reasons and radiation hardness are most important in its selection.

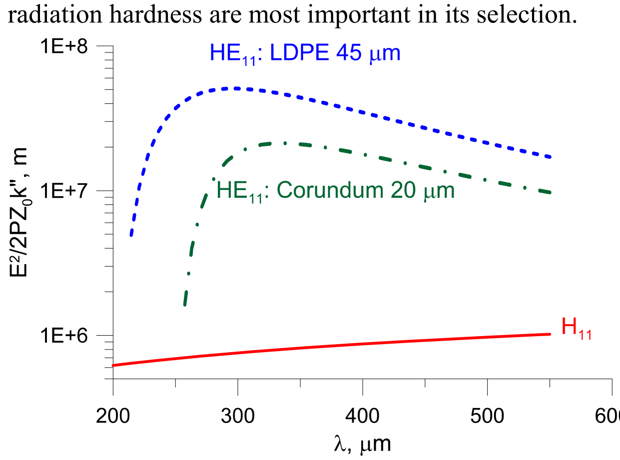

Figure 2: Efficiency of a circular waveguide: all-metal – solid, LDPE coated – dotted, corundum coated – dash-dot.

Losses in a waveguide optical resonator are shown in Fig. 3. If the mirrors are placed close to the waveguide, reflections losses and beyond the mirror ones are absent. In this case the mirrors should be cylindrical for a parallel-plate waveguide and flat in other case. If there is significant distance between a flange and a mirror, the latter should be elliptical for a parallel-plate waveguide and spherical in other cases.

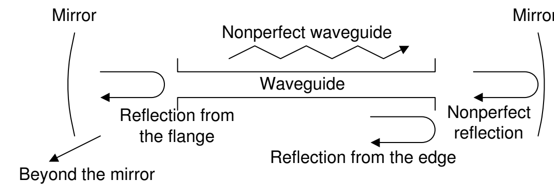

Figure 3: Possible losses in waveguide resonators.

Reflection from a flange is caused by diffraction and depends on the parameter $\kappa = kl^2 / R$, where R is the distance to the mirror. Limits for κ for various losses and field distributions are placed in Table 1.

Table 1: Maximum Allowable κ

Losses \ Distribution	Cos-like	Rectangular
1%	0.64	0.34
10%	2.1	1.06

Most frequent nonuniformity of a waveguide is its variable curvature. Higher order modes are generated in the places where the curvature is changed. These modes damp more rapidly than the fundamental one. Some part of power is also reflected. These losses can be estimated using the following formulae [9]:

$$\cong \frac{0.2376(kl)^6}{(kR_y)^2} \qquad (2)$$

and

$$\cong \frac{4d^2}{3R_x^2} . \qquad (3)$$

The meanings of variables in the formulae above are explained in Fig. 4.

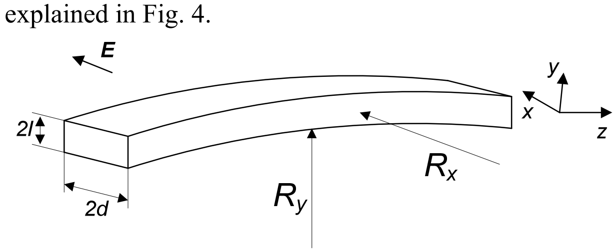

Figure 4: Curvature of a waveguide.

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BEAM INJECTION AND EXTRACTION

Possible injection and extraction schemes depend on the type of the optical resonator. If there are significant distances from the waveguide flanges to the mirrors, the conventional scheme can be used, like in Fig. 5. The advantages of this scheme are that an electron moves in the empty space and the length of the resonator is controlled easily. The main drawback is losses on places with limited aperture, namely mirrors and flanges.

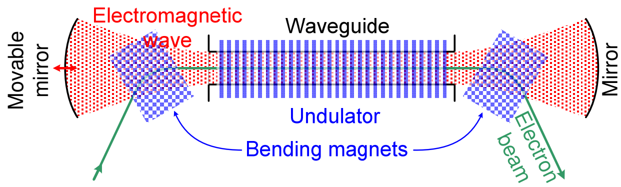

Figure 5: A conventional injection and extraction scheme.

If the mirrors of the optical resonator are adjacent to the waveguide, and the latter is parallel-plate, an injection and extraction scheme could be as in Fig. 6. In this case there is no power loss at the right (as in Fig. 6) waveguide flange. The movable mirror has some small distance to the waveguide flange, so power loss here is unavoidable due to diffraction. Another advantage of this scheme is that it is shorter than the previous one. A drawback is that the waveguide is longer, so power loss in it is bigger.

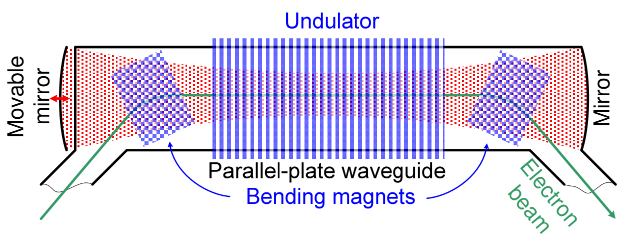

Figure 6: An injection and extraction scheme for a parallel-plate waveguide and adjacent mirrors.

If the average beam power is not so high, a scheme like in Fig. 7 can be used. It does not contain bending magnets. An electron beam is injected into a circular waveguide through a thin mesh. Outcoupling is through the same mesh. A blind movable mirror at the opposite end of the waveguide is simultaneously a beam dump. The main advantage of the scheme is that the waveguide is short and there is no flange power loss simultaneously. Also the resonator length is the shortest. There are some drawbacks too. A gap between the plunger and the waveguide absorbs some small part of electromagnetic power. The mesh mirror also absorbs and scatters some part of incoming electron beam.

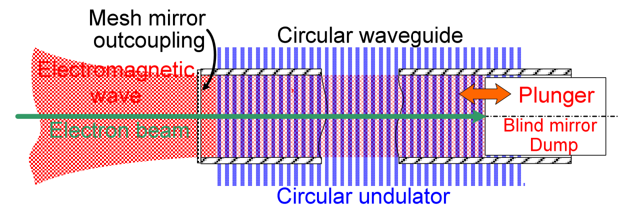

Figure 7: An injection and extraction scheme for a helical geometry and adjacent mirrors.

A ring optical resonator can be used together with the conventional scheme, as in Fig. 8. Its advantage is that all the power losses caused by the waveguide are twice smaller than in the simplest case. The drawbacks are that its alignment is terribly sophisticated and power losses on mirrors are twice bigger.

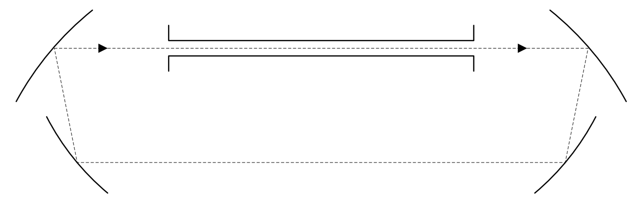

Figure 8: A ring optical resonator.

OUTCOUPLING

The simplest outcoupling is a hole in the centre of a mirror, as in Fig. 9. It is used most frequently in FELs. The main drawback is 50% loss of extracted power, as the hole is a radiator emitting waves both sides equally. Radiation toward the resonator has the pattern almost orthogonal to its fundamental mode if the hole is small enough.

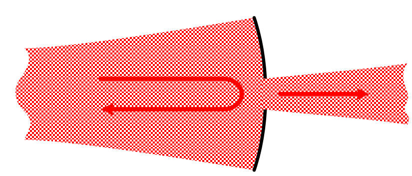

Figure 9: Centre hole outcoupling.

There is a well-known method to solve this problem: the use of huge number of very small radiators instead of large one. This is mesh outcoupling shown in Fig. 10. If the distance between the mesh holes is much smaller than the wavelength, their emission interferes constructively in both directions, and the total pattern is almost equal to this of the incident wave. The transparency of the mesh strongly depends on its period and geometrical transparency. An electron beam of moderate power can be injected through the mesh with moderate loss. The scheme has some drawbacks. The mesh hardly can be shaped well like a solid mirror, so can be flat only. Even in this case it can be easily deform due to non-uniform heating. The mesh transparency significantly depends on the wavelength.

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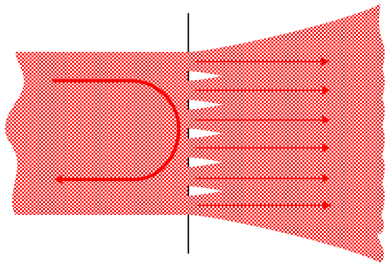

Figure 10: Mesh outcoupling.

One more possibility is an inclined dielectric plate in the way of electromagnetic wave. It reflects a part of wave power out of the resonator. In this case there are two reflecting surfaces. If the plate is thin enough, there is interference between two reflected pulses, that results strong dependency of the outcoupling coefficient on the wavelength. The plate can be made so that the optical paths for the two pulses differ approximately by their length. In this case there is almost no interference, but the pulse length is doubled.

RESONATOR RETUNING

Significant retuning of the optical resonator is necessary when wavelength tuning, as the group velocity in a waveguide depends on the wavelength, and the detuning (the difference between the bunch repetition rate and the appropriate harmonic of the resonator) should be preserved. For example, if one needs to control the wavelength within 200 to 400 µm in a FEL with a parallel-plate waveguide of the height of 5 mm and the length of 3 m, he needs to change the length of the resonator within approximately 1.8 mm. It is comparable to the bunch length of an S-band accelerator and can not be ignored. All the resonators described above have this property.

CONCLUSION

- The design of a THz FEL typically differs from this of a conventional FEL.
- The use of a waveguide seems to be a good idea.
- Several various designs of waveguide resonators are possible. Each one has its own advantages and posers and is intended for appropriate applications.

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