Launch conditions and mode coupling in hollow-glass waveguides

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Abstract. The attenuation and input end heating of hollow-glass waveguides are greatly affected by the way in which the input laser energy is coupled into the guides. A theoretical discussion of coupling conditions is related to waveguide loss and local heating, which can occur when the coupling is not optimized. Our results indicate that the optimum coupling for maximum transmission is not necessarily equivalent to optimum coupling to the lowest order HE_{11} mode. Additionally, it is shown that the input end heating of these waveguides can be reduced substantially with minimal effect on transmission if the waveguide bore size is large.
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1 Introduction

Hollow-glass waveguides that have internal metal and dielectric films are today one of the most attractive means of delivering CO_2 laser power.[1,2] These hollow-glass waveguides, usually with a metallic film of Ag and a single dielectric film of AgI or AgBr, have very low loss[3,4] and high spatial purity of the output beam profile[5] as a result of the smooth inner surface and the high uniformity in cross section of the glass tubing used as the base material. For example, it was shown by Abel et al.[3] and Matsuura et al.[4] that at 10.6 μm, single-dielectric-layer hollow-glass waveguides have measured losses equal to those calculated for the lowest order HE_{11} mode.

Unlike solid-core fibers, the loss in hollow waveguides is highly dependent on the launch conditions. The choice of input coupling lens is, therefore, crucial to achieving total losses in hollow-glass waveguides that approach the theoretical loss of the HE_{11} mode. This paper presents a discussion on the optimum launch conditions for the three most popular bore size (320, 530, and 700 μm) hollow-glass waveguides.

2 Attenuation Coefficients for the HE_{1m} Modes

The theory describing losses in circular hollow waveguides was first thoroughly explored by Marcatili and Schmeltzer[6] in 1964. Their work was followed by Miyagi and Karasawa, who calculated bending losses in these structures.[7] The results of this work give two important relationships for the attenuation coefficient α, which govern the losses in hollow guides, that is,

$$\alpha \propto \frac{1}{a^3} \quad \alpha \propto \frac{1}{R}, \tag{1}$$

where α is the bore diameter and R is the bending radius. These relationships show that the waveguide losses will increase dramatically as the bore size is reduced and that there is an additional loss on bending, which increases as the inverse of the bend radius. In addition, hollow waveguides have the lowest loss for the lowest order waveguide modes. Higher order modes are much more lossy, and therefore, even though the core diameter is often more that 100 times greater than the wavelength, hollow waveguides tend to propagate near single-mode energy because the higher order modes are rapidly attenuated.

In 1984, Miyagi and Kawakami developed equations describing the attenuation coefficient for the special case of a metallic hollow waveguide coated with dielectric films to enhance the reflectivity.[8] For a single dielectric film, the minimum loss occurs when the thickness d is given by

$$d = \frac{\lambda}{2\pi(n_d^2-1)^{1/2}} \tan^{-1}\left[\frac{n_d}{(n_d^2-1)^{1/4}}\right], \tag{2}$$

where n_d is the refractive index of the dielectric film. The assumption is that there is no absorption in the film. Accordingly, Miyagi and Kawakami arrived at the following equation for the attenuation coefficients of the various HE_{nm} waveguide modes:

$$\alpha_{nm} = \left(\frac{u_{nm}}{2\pi}\right)^2 \frac{\lambda^2}{a^3} \left(\frac{n}{n^2+\kappa^2}\right) \times \left\{\frac{1}{2}\left[1+\frac{n_d^2}{(n_d^2-1)^{1/2}}\right]^2\right\}, \quad HE_{nm} \text{ modes}, \tag{3}$$

where n and κ are the real and imaginary parts of the complex index of the metallic guide, u_{nm} is the mth root of the zero-order Bessel function, λ is the wavelength, and a is the bore radius.

In Fig. 1 the attenuation coefficients for the first four HE_{1m} modes in a Ag/AgI hollow-glass waveguide are cal-

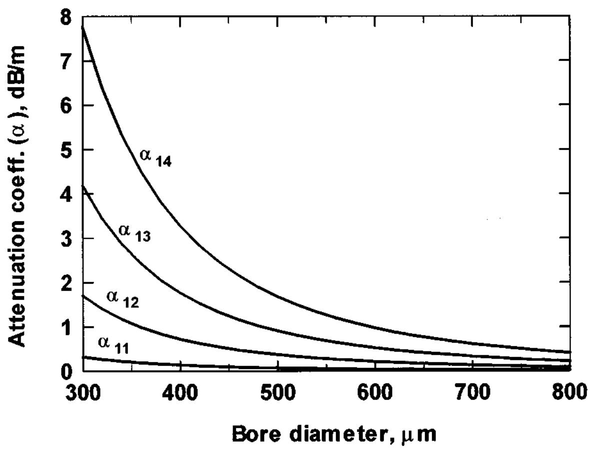

Fig. 1 Calculated attenuation coefficients of the first four HE_{1m} modes in hollow-glass waveguides.

culated as a function of bore diameter using Eq. (3). These theoretical curves show the $1/a^3$ dependence of loss as well as the dramatic increase in loss for the higher order modes. Note that the attenuation of the higher order modes is particularly severe for the small-bore waveguides. Because the higher order modes are so rapidly attenuated, it becomes possible to deliver a near-single-mode beam through the small-bore waveguides.[5] The larger bore waveguides will transmit the higher order modes over longer lengths, but the total loss will be substantially less than for the small-bore waveguides.

3 Coupling Efficiency to the HE_{1m} Modes

When a Gaussian beam is focused into a hollow waveguide on axis, only the HE_{1m} modes are excited. Since the HE_{11} mode has the lowest theoretical loss, it is desirable to know the launching conditions necessary to couple most of the input beam to this mode. The spatial profiles of the HE_{1m} modes in the waveguide can be approximated by the zero-order Bessel function, that is

$$E(r)=E_0 J_0\left(u_m \frac{r}{a}\right), \tag{4}$$

where $0\leq r<a$; and a Gaussian beam focused to a $1/e^2$ waist ω can be expressed by

$$E(r)=E_0 \exp\left(-r^2/\omega^2\right). \tag{5}$$

The power coupling efficiency of the incident beam to each HE_{1m} waveguide mode can be expressed by the overlap integral[9–11]

$$\eta_m=\frac{\left\lfloor \int_0^a \exp\left(-r^2/\omega^2\right) J_0\left(u_m \frac{r}{a}\right) r\,\mathrm{d}r\right\rfloor^2}{\int_0^\infty \exp\left(-2r^2/\omega^2\right) r\mathrm{d}r \int_0^a J_0^2\left(u_m \frac{r}{a}\right) r\,\mathrm{d}r}. \tag{6}$$

This equation describes the amount of power coupled to the HE_{1m} waveguide modes for a given spot size to bore size ratio ω/a. Using Eq. (6), we calculate that the coupling

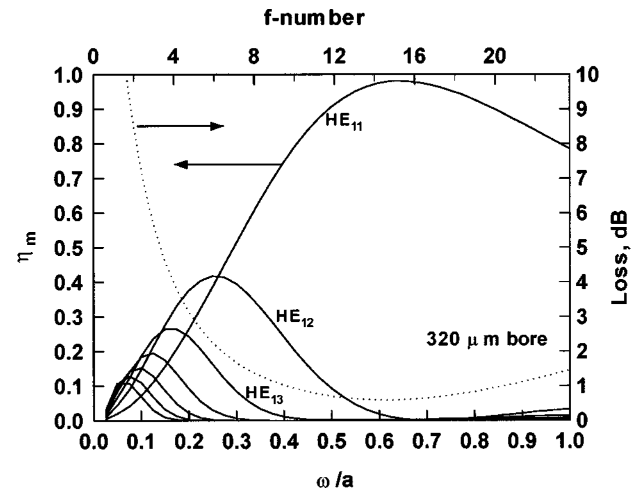

Fig. 2 Calculated coupling coefficients (solid curves) and total loss (dotted curve) of a 1-m-long, 320-μm-bore, hollow-glass waveguide.

efficiency to the lowest loss HE_{11} mode is highest with a beam waist to bore radius ratio, $\omega/a\cong 0.64$. Under these conditions $\eta_1=98.1\%$ and $\eta_2=0.5\%$. We find it more practical to define the coupling efficiency as a function of f-number$=f/D$, where f is the focal length of the lens used to couple the laser to the waveguide, D is the laser beam diameter, and $f/D=\pi\omega/2\lambda$. Figures 2–4 show coupling efficiencies of the first seven HE_{1m} modes in hollow-glass waveguides, respectively, as a function of launch conditions. In addition, the overall loss calculated as a sum of the first seven modes is also given in these figures. The optimum coupling to the HE_{11} mode occurs at an f-number launch of $\sim f/16$, $\sim f/26$, and $\sim f/35$ for the 320-, 530-, and 700-μm-bore waveguides, respectively. At small f-numbers more power is coupled to the higher order modes, and at larger f-numbers the focused spot becomes larger than the waveguide bore, and the beam is clipped by the waveguide walls.

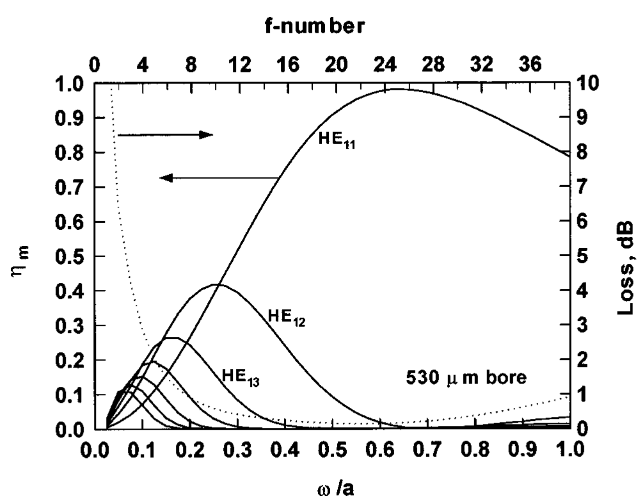

Fig. 3 Calculated coupling coefficients (solid curves) and total loss (dotted curve) of a 1-m-long, 530-μm-bore, hollow-glass waveguide.

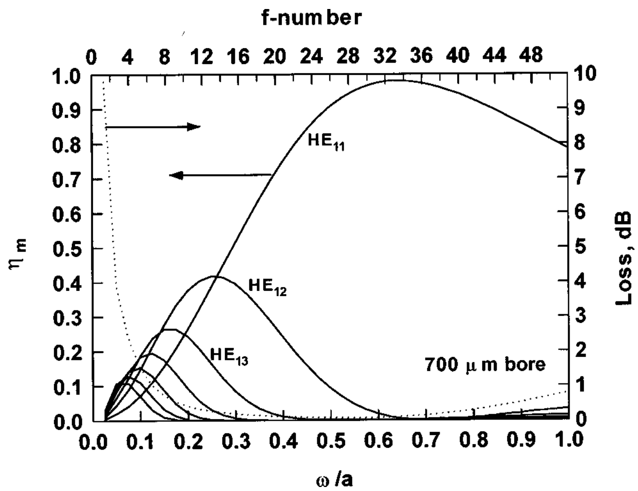

Fig. 4 Calculated coupling coefficients (solid curves) and total loss (dotted curve) of a 1-m-long, 700-μm-bore, hollow-glass waveguide.

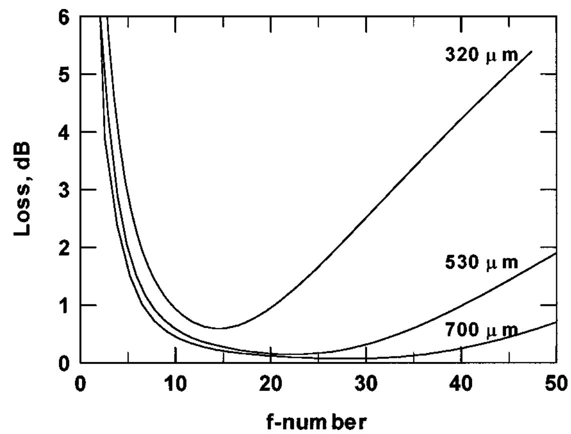

Fig. 5 Minimum-loss coupling conditions for the 1-m-long, 320-, 530-, and 700-μm-bore hollow-glass waveguides.

4 Total Loss in Hollow-Glass Waveguides

Choosing an input lens that gives optimum coupling to the HE_{11} mode does not necessarily produce the lowest loss condition. As noted in Fig. 1 the higher order modes have larger attenuation coefficients, particularly for the small-bore waveguides. For the large-bore waveguides, however, the increase in loss due to higher order mode propagation is small. It becomes necessary, therefore, to couple as much power as possible to the HE_{11} mode (at $\omega/a \cong 0.64$) for the small-bore waveguides. In the case of the large-bore waveguides, however, the total loss can be reduced by under coupling to the waveguide; that is, by using a lens that produces a spot smaller than is optimum for coupling to the HE_{11} mode the amount of power that is clipped by the waveguide wall can be reduced, and the transmission will increase. Therefore, to achieve minimum loss in the large bore waveguides the coupling conditions should be such that $\omega/a \cong 0.55$ not 0.64 (Refs. 12–14).

To calculate the theoretical transmission of a hollow-glass waveguide one needs to take into account both the attenuation of and coupling efficiency to each of the modes. Accordingly, the transmission in a length z, P_z, can be expressed as

$$P_z = \sum_m \eta_m \exp(-2\alpha_m z), \tag{7}$$

where $2\alpha_m$ is power attenuation coefficient. This results from squaring the electric field to get the intensity. It is particularly important to sum over all possible modes when calculating a theoretical loss for waveguides used on industrial lasers or under poor launch conditions since many higher order modes can be excited. On a laser with a TEM_{00} output mode it is sufficient to take into account only the contribution from the HE_{11} and HE_{12} modes if care has been taken to launch correctly. Figure 5 shows the coupling conditions necessary to achieve minimal loss through 1-m-long, 320, 530, and 700-μm-bore hollow-glass waveguides. Maximum transmission occurs at an f-number launch of $\sim f/15$ ($\omega/a = 0.614$), $\sim f/22$ ($\omega/a = 0.569$), and $\sim f/30$ ($\omega/a = 0.544$) for the 320, 530, and 700-μm-bore hollow-glass waveguides, respectively. Note that the launch condition necessary for maximum transmission requires a smaller f-number launch than for optimum coupling to the HE_{11} mode. The difference depends on bore size and is more severe for the larger bore waveguides. Of course, as the waveguide length is increased, the launch condition necessary for maximum transmission approaches $\omega/a = 0.64$, that is, optimum coupling to the HE_{11} mode. However, the results presented here for a 1-m-long waveguide remain nearly the same for waveguides up to $\sim$3 m long.

A more graphic display of the effect of the HE_{11} and HE_{12} modes on loss for the three bore sizes is obtained by considering the loss with optimal coupling to the HE_{11} and with optimal coupling to the sum of the HE_{11} and HE_{12} modes. The results of these calculations are shown in Fig. 6 for the different bore sizes. For the small 320-μm bore, the lowest loss is obtained for the HE_{11} bore because the HE_{12} mode is very lossy. However, for the large 700-μm bore,

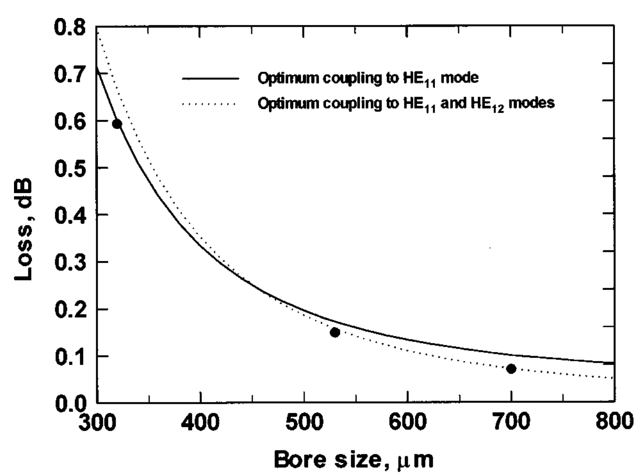

Fig. 6 Total loss as a function of bore size under the launch condition that maximizes the amount of energy coupled to just the HE_{11} mode (solid curve) and that maximizes the amount of energy coupled to both the HE_{11} and HE_{12} modes (dotted curve). The solid circles represent the calculated minimum loss for the three different bore size waveguides.

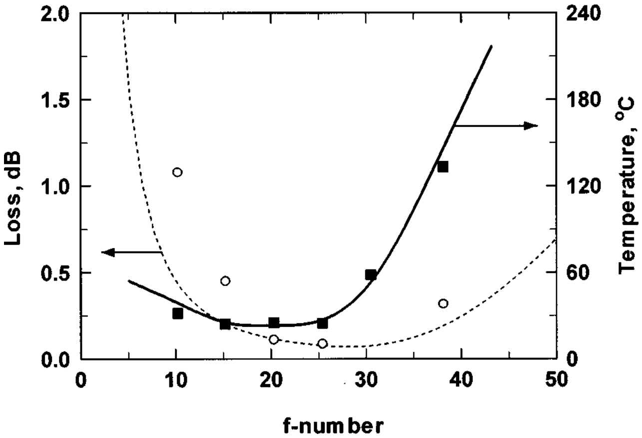

Fig. 7 Calculated (solid curve) and measured (solid squares) input-end temperature as well as calculated (dashed curve) and measured (open circles) total loss of a 1-m-long, 700-μm-bore hollow-glass waveguide under different launch conditions.

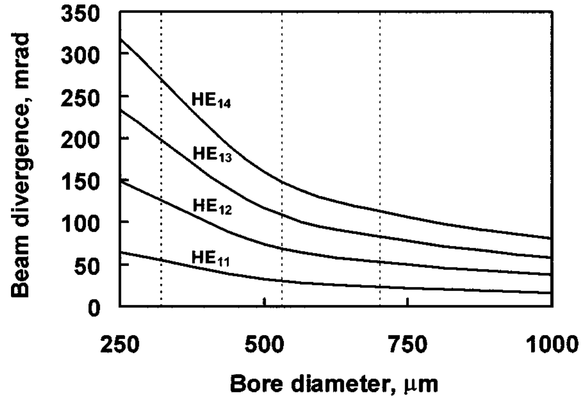

Fig. 8 Calculated beam divergence of the first four HE_{1m} modes exiting a hollow-glass waveguide. The vertical dashed lines indicate the 320-, 530-, and 700-μm-bore waveguides.

the lowest loss is achieved by coupling to both the HE_{11} and HE_{12} modes. Again this is a result of the lower relative loss of the HE_{12} mode for larger bore size waveguides.

5 Input-End Heating Effects and Output Beam Divergence

The input end of hollow-glass waveguides can melt with only a few watts of CO_2 laser power incident on the waveguide wall. For input powers greater than ~50 W, it is important to consider how much power strikes the waveguide wall for a given transmission and launch condition.[13,15] For example, we were successful in delivering over 1000 W of CO_2 laser power through a 700-μm-bore hollow-glass waveguide only after the input end was carefully protected with a reflective cone.[16] To study these effects more in depth we measured the temperature at the input end of the guides under different launch conditions. A 1-m-long, 700-μm-bore waveguide with a CO_2 laser input power of ~20 W was used for the temperature study. The input-beam profile was measured with a Pyrocam 128 $\times$128 pyroelectric array (Spiricon, Inc., Logan, Utah) and was very nearly Gaussian. The temperature 0.5 cm from the input end of the waveguide was measured with a thermocouple in contact with the outer wall of the waveguide. Sufficient time was allowed for the temperature to reach steady state before the measurement was taken. The results are shown in Fig. 7. Referring back to the data in Fig. 5, we see that a ~$f/30$ launch will produce the lowest loss for this bore size. But the data in Fig. 7 show that the temperature of the input end will be higher with this launch condition than if a smaller *f*-number, for example, $f/25$, is used. Specifically, the input end of the 700-μm-bore waveguide reached a steady state temperature of ~60°C with an *f*-number launch of $f/30$. With an *f*-number launch of $f/39$, the input end of this waveguide was above 130°C, but with an *f*-number launch of between $f/15$ and $f/25$ we were able to reduce the steady state heating of the input end to <30°C. The high-input-end temperatures result from some input beam clipping. While this would not necessarily be important for low power applications, it is a concern for powers greater than approximately 5 to 10 W. For these powers it is better to use a slightly lower *f*-number even though the guide losses will be somewhat higher.

The output beam divergence of the hollow glass waveguides also depends on the modes propagating in the guide as well as the bore size. The HE_{1m} modes will couple to free-space modes with a half-angle beam divergence θ given by[17]

$$\theta_m \cong \sin\,\theta_m = \frac{u_m \lambda}{2\pi a}. \tag{8}$$

Calculations for the beam divergence of the first four HE_{1m} modes are given in Fig. 8 for different bore sizes. As expected, the lowest order mode gives the smallest beam divergence. This data agrees well with the value ~20 mrad measured for the 700-μm-bore waveguide under optimal launch conditions. In Fig. 9, we show our experimental results, again measured with a Pyrocam 128$\times$128 pyroelectric array, which confirm the results of the calculations shown in Fig. 8. For the 700-μm-bore waveguide smaller *f*-number launch conditions produced greater beam divergence. The optimum launch conditions ranging between

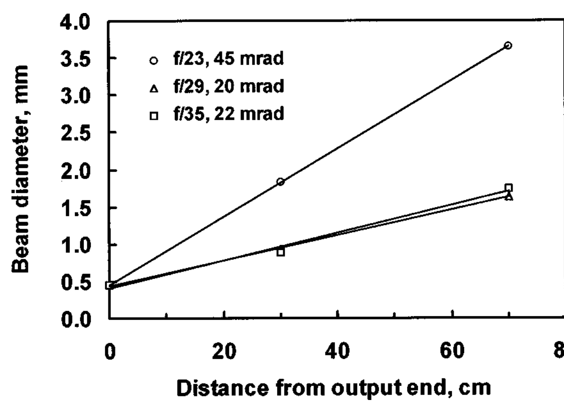

Fig. 9 Measured beam divergence exiting a 1-m-long, 700-μm-bore hollow-glass waveguide with an *f*/23 (circles), *f*/29 (diamonds), and *f*/35 (squares) launch. The solid curves represent best-fit lines through the data.

$f/29$ and $f/35$ produced the smallest beam divergence of approximately 20 mrad. When higher order modes are coupled into the guides with the $f/23$ launch then the beam divergence is 45 mrad. For many applications, such as in cutting where small spot sizes are desirable, it is important to have small beam divergence and, therefore, the lowest order modes should be launched and propagated.

6 Conclusions

Hollow-glass waveguides are excellent candidates for the delivery of CO_2 laser energy. Because of the extremely smooth wall of these waveguides, near-theoretical losses and near-single-mode output can be achieved if the proper coupling conditions are used. We have presented a theoretical discussion that describes how the minimum loss condition may be obtained for the three most popular bore size hollow-glass waveguides: 320, 530, and 700 μm.

In general, the coupling conditions required to achieve maximum transmission through these hollow-glass waveguides is such that $\omega/a<0.64$ not $\omega/a=0.64$, as is generally quoted in the literature. A smaller input spot size reduces the amount of energy that is clipped by the waveguide wall but increases the amount of energy that is coupled to higher order modes. In large-bore waveguides, the attenuation coefficients of the higher order modes are not significantly greater than that of the HE_{11} mode, so decreasing the input beam spot size to eliminate clipping of the beam does not have an appreciable effect on the total loss.

Furthermore, it is crucial in high-power applications to keep the laser energy from hitting the waveguide walls because immediate and disastrous failure will occur. Heat produced by the absorption of power uniformly along the waveguide is easily removed by convective cooling. It is, therefore, possible to eliminate the chance of damaging the input end by reducing the input beam spot size. The smaller *f*-number launch necessary to get the smaller focused spot will excite higher order modes, and this will increase the waveguide's total loss, but the power lost will be distributed more evenly along the length of the waveguide. Finally, the output beam divergence is smallest for the lowest order mode.

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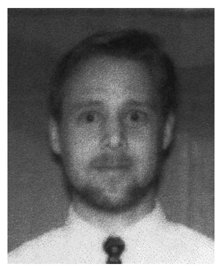

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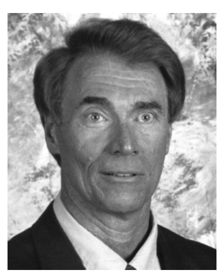

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