# High quantum efficiency of near-infrared emission in bismuth doped AlGeP-silica fiber

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A self-calibrating method is described for measuring the radiative quantum efficiency (QE) in doped optical fibers. The method uses an integrating sphere to collect the fluorescence from the fiber, with pump light transmitted through the fiber end serving as a reference. QE measurements for a 780 or 808 nm pump were made on bismuth-doped AlGeP-silica fibers prepared by aerosol deposition. For both wavelengths, a value of QE=1.0±0.05 was obtained. Fluorescence was observed in two bands centered around 800 and 1300 nm, and the relative strength of these bands was found to vary with the pump wavelength. © 2009 Optical Society of America

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An efficient broadband light source in the 1300 nm region is of interest for interferometric sensing applications such as optical coherence tomography (OCT), as well as for optical communications [1,2]. A promising new material for these applications is bismuth-doped glass, which has been shown to have a very broad near-IR emission when pumped in the visible or near-IR range [3]. Although the spectral dependence and the decay time of the bismuth emission have been studied for a variety of compositions in both bulk glass [4–7] and fiber [8,9], there are only a few reports of absolute quantum efficiency (QE) measurements, and those few have only been for bulk glass samples [6,7]. The knowledge of the radiative efficiency of the bismuth centers is important for characterizing the performance of practical devices, and also for obtaining a better understanding of the fundamental nature of the luminescent centers. In this work, we describe a self-calibrating method for determining the radiative QE, especially developed for measurements on fibers. The application of this technique to bismuth-doped AlGeP-silica fibers pumped around 800 nm reveals a QE close to unity.

The basic principle of the method is illustrated in Fig. 1. The fiber is inserted into one port of an integrating sphere (IS) and coiled loosely inside, with the far end of the fiber pushed back out the same port and mounted in a rotatable chuck. The IS creates a uniform light energy density from the fluorescence emitted from the sides of the fiber, and a fraction of this light is collected by a cooled Ge detector attached to a second port. The signal from the Ge detector is measured for two positions of the fiber end, which we call A and B. First, the chuck is rotated so that the light emitted from the fiber end is directed away from the IS (position A), so the signal $S_A=S_{\text{fluor}}$ is due only to fluorescence emitted from the sides of the fiber. Next, the chuck is rotated and positioned so that the light emitted from the fiber end is aimed back into the IS (position B), and the signal $S_B=S_{\text{fluor}}+S_{\text{out}}$ is then due to both side fluorescence and the pump light that exits the fiber end. For our measurements, the amount of fluorescence trapped in the fiber core and emitted from the end is much smaller than either the total side fluorescence or the transmitted pump light, and can be neglected. The ratio of the fluorescence signal to the transmitted pump signal is then $S_{\text{fluor}}/S_{\text{out}}=1/(r-1)$, where $r=S_B/S_A$ is the measured ratio of signals.

To determine the QE from the measured signal ratio, we first need to take into account the spectral dependence of the fluorescence $P_\lambda(\lambda)$ and the spectral response of the detection system $R(\lambda)$. We determined $P_\lambda(\lambda)$ in a separate experiment by passing the side emission from the fiber through a monochrometer. The results are shown in Fig. 2, corrected to give the relative power emitted per wavelength interval. The emission is in two bands, which we denote as the 800 and 1300 nm bands. A small contribution from the scattered pump light is also seen in both spectra. The decay time of the 1300 nm band is nonexponential and can be characterized by the first $e$-folding time $t_1$ (time to decay by $e^{-1}$) or by the stretched exponential $\exp[-(t/\tau)^\beta]$. The decay time varies across the band, with $(t_1,\tau,\beta)=(660,630,0.80)$ at 1150 nm and $(t_1,\tau,\beta)=(890,885,0.86)$ at 1300 nm. This varia-

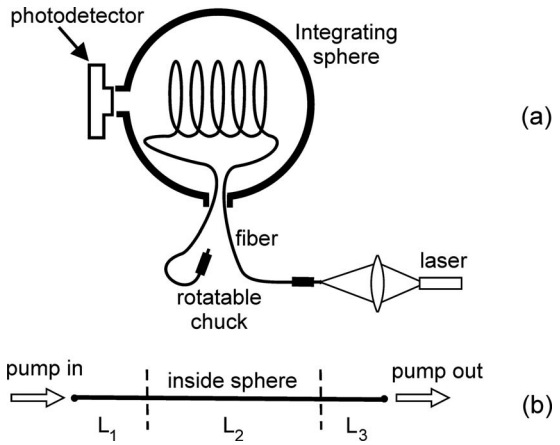


Fig. 1. (a) Experimental setup for measuring the QE. (b) Definition of fiber lengths.

 

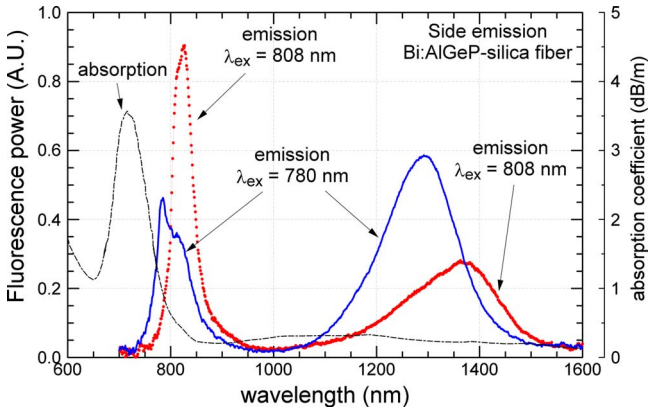


Fig. 2. (Color online) Absorption coefficient and fluorescence spectra for Bi:AlGeP-silica fiber pumping at 780 or 808 nm.

tion is consistent with a multiple-site model in which Bi centers occupy either site A (pumping at ~500, ~700, or ~1000 nm) or site B (pumping at ~800 nm) [6,7]. The decay of the 800 nm band is much faster, limited by the time resolution of our measurement (<4 $\mu$s). In making the spectral and QE measurements, we used a low chopping frequency (15 Hz) so the fluorescence from both bands was nearly in steady state.

The system spectral response $R(\lambda)$ is defined as the detector voltage divided by the optical power emitted from the fiber. This depends on two things: the "throughput" of the IS (caused by the varying reflectivity of the inner surface with $\lambda$) and the responsivity of the detector (signal voltage/incident power). We measured the spectral response of the IS by comparing the spectrum of a white light source that has passed through the IS to the spectrum of the same source when it directly illuminates the monochrometer slits. The spectral response of the cooled Ge detector was measured by comparing its signal to that of a spectrally flat pyroelectric detector, when using a white light source. Multiplying the IS throughput by the detector spectral response gives the overall system response $R(\lambda)$. Only relative values of $R(\lambda)$ are needed, since any arbitrary scale factor cancels out when taking the ratio of signals.

The signal obtained in measurement A can now be written as $S_A = \int R(\lambda) P_\lambda(\lambda) d\lambda$, where the integral is over both the 800 and 1300 nm bands. In measurement B, the signal from the transmitted pump power $P_{out}$ is added, $S_B = S_A + R(\lambda_p) P_{out}$, where $R(\lambda_p)$ is the system response at the pump wavelength $\lambda_p$. The ratio of signals can then be written as

$$r = \frac{S_B}{S_A} = 1 + \frac{R(\lambda_p) P_{out}}{\int R(\lambda) P_\lambda(\lambda) d\lambda} = 1 + \frac{P_{out}}{D P_{emit}}, \qquad (1)$$

where $P_{emit} = \int P_\lambda(\lambda) d\lambda$ is the total emitted fluorescence power. The dimensionless parameter $D \equiv \int R^*(\lambda) \rho(\lambda) d\lambda$ has also been defined, where $\rho(\lambda) \equiv P_\lambda(\lambda)/P_{emit}$ is the normalized fluorescence and $R^*(\lambda) \equiv R(\lambda)/R(\lambda_p)$. Assuming that Beer's law holds, the pump power absorbed in the fiber section $L_2$ can be written as $P_{abs} = F P_{out}$, where $F \equiv \{\exp[\alpha(L_2+L_3)] - \exp[\alpha L_3]\}(1+\varepsilon)/T$. In this equation, $T = 0.96$ is the fraction of the pump light transmitted through the fiber end and $\varepsilon = (1-T)\exp[-\alpha(L_2+2L_3)]$ takes into account the pump light reflected from the fiber end and absorbed inside the IS. Combining the above, the power efficiency is $P_{emit}/P_{abs} = 1/[DF(r-1)]$. To obtain the QE, we use this power efficiency along with the photon absorption and emission rates $\mathcal{R}_{abs} = P_{abs}(\lambda_p/hc)$ and $\mathcal{R}_{emit} = (1/hc)\int P_\lambda(\lambda)\lambda d\lambda$ to obtain

$$QE \equiv \frac{\mathcal{R}_{emit}}{\mathcal{R}_{abs}} = \frac{\bar{\lambda}_{em}}{\lambda_p} \frac{1}{DF(r-1)}, \qquad (2)$$

where $\bar{\lambda}_{em} \equiv \int \rho(\lambda)\lambda d\lambda$ is the average emission wavelength. Note that Eq. (2) requires only relative spectral measurements to determine the absolute QE.

The procedure described above was applied to bismuth-doped AlGeP-silica fiber prepared by an aerosol deposition technique [10]. The average core diameter of $\approx 11$ $\mu$m and the index difference of $\Delta n \approx 0.007$ correspond to a calculated NA $\approx 0.145$ and a cutoff wavelength of $\lambda_c \approx 2.1$ $\mu$m, making it a few-mode fiber in the wavelength range of interest. The absorption spectrum $\alpha(\lambda)$ shown in Fig. 2 was measured with a white light source using the cutback method. This shows not only the absorption $\alpha_{Bi}(\lambda)$ expected from Bi, but also an additional longer wavelength absorption $\alpha_{imp}(\lambda)$ that we confirmed, by preparing an identical fiber without Bi, as arising from some type of impurities in the glass. In determining the Bi QE, we only want to consider the power absorbed by the Bi centers, not the impurities. To correct for this, we divided the right-hand side of Eq. (2) by $\alpha_{Bi}(\lambda_p)/\alpha(\lambda_p)$ for the experiments reported here. Since it is important to know the absorption coefficient $\alpha(\lambda_p)$ accurately, we made a separate measurement of this by launching the pump light into the fiber and passing a straight section of fiber through the IS between ports on opposite sides of the sphere. The fiber was pulled through in steps, and the total fluorescence signal was measured at each step. The signal versus fiber position was found to be exponential over a length of 5 m, which is consistent with Beer's law. This also indicates that there is no significant depletion of the Bi ground state under these conditions. The signal ratio $r = S_B/S_A$ was then measured for the pump wavelengths and values of $L_2$ and $L_3$ indicated in Table 1. The value of $r$ increased at higher pump powers, indicating bleaching of the Bi ground state absorption. To minimize this effect, we used the low-power limit of $r$ for the QE calculations.

The results of the QE measurement are given in Table 1, and for both the 780 and 808 nm pump wavelengths are consistent with QE = 1.0 ± 0.05. This indicates that there is very little nonradiative quenching of the 1300 nm emitting level, which is in accord with previous observations that the near-IR fluorescence lifetime is temperature independent [6,9]. Also listed in Table 1 is the branching ratio $\beta_{800}$, defined as the probability that, when an excited Bi

**Table 1. Parameters Used in Calculating the QE of Bi Doped Glass Using Eq. (2)**

| Parameter | Trial 1 | Trial 2 | Trial 3 | Trial 4 |
|---|---|---|---|---|
| $\lambda_p$ (nm) | 808 | 780 | 780 | 780 |
| $\lambda_{em}$ (nm)[a] | 823/1370 | 811/1291 | 811/1291 | 811/1291 |
| $\beta_{800}$ | 0.315 | 0.166 | 0.166 | 0.166 |
| $\bar{\lambda}_{em}$ (nm) | 1111 | 1160 | 1160 | 1160 |
| $D$ | 1.485 | 1.92 | 1.92 | 1.92 |
| $\alpha$ ($m^{-1}$) | 0.104 | 0.223 | 0.223 | 0.223 |
| $\alpha_{imp}$ ($m^{-1}$) | 0.02 | 0.015 | 0.015 | 0.015 |
| $L_2$ (m) | 6 | 6 | 2 | 1 |
| $L_3$ (m) | 0.5 | 0.5 | 0.5 | 1.5 |
| $r$ | 2.17 | 1.25 | 2.2 | 3.34 |
| QE | 1.01 | 1.00 | 1.03 | 0.96 |

[a]Wavelengths of peak emission in the 800 and 1300 nm bands.

center radiates, it emits into the 800 nm band. It is notable that $\beta_{800}$ is quite different for the pump wavelengths of 780 and 808 nm. One way to understand this is in terms of an energy level diagram like that of Fig. 3. Level 3 is excited by the 800 nm pump light and decays either radiatively to the ground state (with probability $\beta_{800}$) or nonradiatively to level 2. From level 2, the decay is (according to our results) mostly radiative. The branching ratio $\beta_{800}$ depends on the ratio of the $3 \rightarrow 1$ radiative rate to the $3 \rightarrow 2$ nonradiative rate, and these rates are likely to be sensitive to the local environment of the Bi center. Varying the pump wavelength from 780 to 808 nm will change the proportion of excited centers in sites A and B and, since these two sites present a different local environment for the active center, this would cause $\beta_{800}$ to be different. Recent experimental and theoretical works [11] suggest that these levels may be molecular orbital states of the $BiO_4$ complex, with both singlet and triplet components, rather than the energy levels of an isolated Bi center [4]. In this case the high QE and the long radiative lifetime of the emission from level 2 would be a consequence of the low probability for triplet→singlet decay. The validity of the experimentally measured QE in this work is, however, independent of the exact nature of the Bi center.

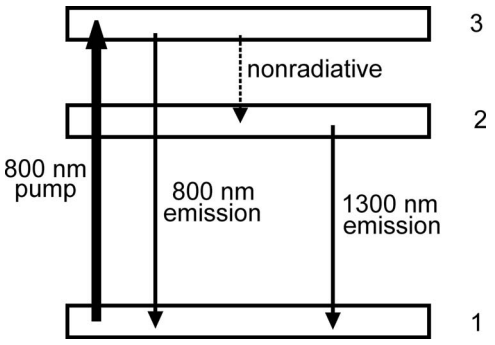


Fig. 3. Possible energy level scheme for 800 and 1300 nm emissions in Bi:AlGeP-silica fiber.

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