

**1.7 μm Excited state absorption measurement in erbium-doped
glasses**

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We have measured, for the first time, the complete 1.7 μm excited state absorption spectrum in erbium doped glasses. The spectrum is obtained by measuring the gain of an erbium doped waveguide in the 1400-1800 nm region. Using the measured spectra, we estimate the 1.5 μm uniform upconversion rate by calculating the spectral overlap between the 1.5 μm emission and 1.7 μm ESA cross sections. The technique is applied to erbium-doped, ion-exchangeable silicate glasses, yielding upconversion constants in the range of $1-10 \times 10^{-18} \text{ cm}^3/\text{s}$.

Planar, erbium-doped, glass waveguide amplifiers are important components in the development of integrated optical communication circuits at 1.5 μm . Such devices must achieve high gains in short lengths and thus require high erbium concentrations ($>10^{19} \text{ cm}^{-3}$). At these doping levels, however, the amplifier gain and efficiency are degraded by ion-ion interactions in the form of uniform and clustered upconversion [1]. Upconversion is a problem in erbium-doped glasses because the 1.5 μm (${}^4I_{13/2} \rightarrow {}^4I_{15/2}$) emission and 1.7 μm (${}^4I_{13/2} \rightarrow {}^4I_{9/2}$) excited-state absorption (ESA) spectra overlap. This overlap allows two excited, neighboring, erbium ions to exchange energy: one ion relaxes nonradiatively to the ground state, ${}^4I_{15/2}$, and the other one rises to the higher state, ${}^4I_{9/2}$. This process, which results in nonradiative quenching of the excited population, is accentuated by the fact that erbium ions may cluster in the glass host, in which case the ion-ion interactions become possible even at low erbium concentrations ($\sim 10^{18} \text{ cm}^{-3}$). Although clustering can in principle be eliminated, uniform upconversion cannot be avoided and thus presents a fundamental limit to the amplifier performance. It is therefore important to identify the glass hosts in which this effect is minimized.

The uniform upconversion rate in erbium-doped glasses may be determined experimentally from fluorescence [1] and lifetime decay [2,3,4] measurements. Alternatively, it may be determined from first principles of energy transfer by calculating the

spectral overlap between the 1.5 μm emission and 1.7 μm ESA spectra. This approach, which is of fundamental interest, requires accurate measurement of the ESA cross section. To this date, only Wyatt [5] has attempted to measure the 1.7 μm ESA spectrum in erbium-doped glasses. However, his measurements did not have the accuracy necessary to allow calculation of the spectral overlap.

In this letter, we present the first accurate measurements of the full 1.7 μm ESA spectrum in erbium-doped glasses, and use the measured spectra to estimate the uniform upconversion rate. The ESA spectrum is obtained by measuring the gain of an erbium-doped waveguide in the 1400-1800 nm region. Applying Dexter's [6] principles of energy transfer to the limit of high erbium concentrations, we estimate the uniform upconversion rate in the erbium-doped glass by calculating the spectral overlap between the measured emission and ESA cross-sections. The technique is applied to erbium-doped silicate glasses suitable for the development of ion-exchanged waveguide amplifiers. For these glasses, we calculate upconversion constants in the range of $1-10 \times 10^{-18} \text{ cm}^3/\text{s}$, which are consistent with upconversion effects reported in the literature [3,4].

The theory of the ESA measurement can be briefly explained as follows. Consider a signal of wavelength λ ($1400 \text{ nm} \leq \lambda \leq 1800 \text{ nm}$) propagating through an erbium-doped waveguide of length L . Suppose that the signal transmission is measured under pumped and

unpumped conditions, with $T_p(\lambda)$ representing the former and $T_o(\lambda)$ representing the latter. In the presence of ESA, it is a simple task to show that the ESA cross section, $\sigma_{esa}(\lambda)$, is given by [5]

$$\sigma_{esa}(\lambda) = \frac{-1}{N_2^{eff} L} \left(\ln \left(\frac{T_p(\lambda)}{T_o(\lambda)} \right) - N_2^{eff} L [\sigma_a(\lambda) + \sigma_{em}(\lambda)] \right) \quad 1$$

where $\sigma_a(\lambda)$, and $\sigma_{em}(\lambda)$ are the 1.5 μm absorption and emission cross sections, respectively, and N_2^{eff} is the effective concentration in the excited state, ${}^4I_{13/2}$. N_2^{eff} is defined as

$$N_2^{eff} \equiv \frac{\int_{-\infty}^{\infty} N_2(x,y) s(x,y) dx dy}{\int_{-\infty}^{\infty} s(x,y) dx dy}, \quad 2$$

where $s(x,y)$ is the transverse mode profile of the signal and $N_2(x,y)$ is the concentration of erbium ions in the excited state. Equation (2) takes into account the variation of the excited erbium population across the waveguide and neglects the wavelength dependence of N_2^{eff} under the assumption that the signal mode profile does not change appreciably over the wavelength range of interest.

To obtain the ESA spectrum, the pumped, $T_p(\lambda)$, and unpumped, $T_o(\lambda)$, transmission spectra are measured in the 1400-1800 nm wavelength region. The absorption cross section, $\sigma_a(\lambda)$, is determined from transmission measurements performed on bulk

samples with knowledge of erbium concentration (i.e., %wt Er₂O₃) and glass density. This cross section is verified by absorption measurements made on the waveguide. The relative shape of the emission cross section, $\sigma_{em}(\lambda)$, is obtained by measuring the 1.5 μm fluorescence spectrum, $f(\lambda)$, which in bulk media is related to the emission cross section by $\sigma_{em}(\lambda) \propto \lambda^5 f(\lambda)$ [7]. The two unknowns, N_2^{eff} and the peak value of $\sigma_{em}(\lambda)$, are determined by least-squares fitting the function $W(\lambda) \equiv N_2^{eff} L[\sigma_a(\lambda) + \sigma_{em}(\lambda)]$ to the measured 'gain', $\ln(T_p(\lambda)/T_o(\lambda))$, in the wavelength region where there is no ESA (i.e., $\lambda \leq 1600\text{nm}$). The residual difference between the transmission data, $\ln(T_p(\lambda)/T_o(\lambda))$, and the function $W(\lambda)$ reveals the ESA spectrum, as described by equation (1). Note that this technique yields not only the relative, but also the absolute ESA and emission cross sections. Furthermore, note that McCumber theory [8] was not used to obtain the absolute emission cross section because it is not as accurate at the long-wavelength tail of the spectrum, the region of interest to us.

Figure 1 shows the experimental apparatus used in the transmission measurement. Waveguides were fabricated in our silicate glasses by thallium-exchange. A white light source provided the signal and a 980nm Ti:Sapphire laser served as the pump source. The pump and signal were combined through a WDM fiber coupler and launched into the Er-doped waveguide. The transmitted signal was collected, passed through a pump-blocking filter and a monochromator, and finally detected with a low-noise

InGaAs detector. Figure 2 shows the measured 'gain', $\ln(T_p(\lambda)/T_s(\lambda))$, and the fitted function, $W(\lambda)$, for a 2%wt Er_2O_3 -doped barium silicate (glass A). The fit was made in the 1450-1600 nm wavelength region. As the figure shows, the function $W(\lambda)$ fits the experimental data closely. Figure 3 shows the normalized, smoothed ESA spectrum obtained after subtracting the curves in figure 2, as well as the normalized emission cross section. The absolute peak values of the cross sections are listed in table I. Figure 4 shows the result obtained for an alumino-phosphosilicate (glass B). The higher noise level in the measured ESA spectrum of this glass was due to its lower erbium concentration (0.5%wt Er_2O_3).

In order to check the validity of our results, we compared the oscillator strengths of the measured ESA spectra to those predicted from Judd-Ofelt theory. Although the oscillator strength does not give information on the shape of the ESA spectrum or its peak value, it does provide information on its transition strength. The measured oscillator strength, f_{exp} , is defined in MKS units as [9]

$$f_{\text{exp}} \equiv \frac{4\epsilon_0 mc^2}{e^2} \int \frac{\sigma(\lambda)}{\lambda^2} d\lambda \quad 3$$

where λ is the wavelength of the transition, ϵ_0 is the free-space permittivity, c is the speed of light, and m and e are the

electron mass and charge, respectively. The oscillator strength, f_{JO} , predicted from Judd-Ofelt theory is given by [9]

$$f_{JO} = f_{md} + \frac{8\pi^2 mc}{3h\lambda} \frac{1}{(2J+1)} \frac{(n^2+2)^2}{9n} \sum_{i=2,4,6} \Omega_i [U^{(i)}]^2 \quad 4$$

where f_{md} is the magnetic dipole contribution to the oscillator strength, n is the index of refraction, J is the total angular momentum of the initial state, $[U^{(i)}]^2$ ($i=2,4,6$) are the matrix elements for the transition, and Ω_i ($i=2,4,6$) are the Judd-Ofelt coefficients for the erbium-doped glass. For the ${}^4I_{13/2} \rightarrow {}^4I_{9/2}$ ESA transition in erbium, $\lambda = 1.7 \mu\text{m}$, $J = 13/2$, $[U^{(2)}]^2 = 0.0003$, $[U^{(4)}]^2 = 0.0087$, and $[U^{(6)}]^2 = 0.71$ [9]. The Judd-Ofelt coefficients for our glasses were obtained by measuring the 980, 650, 520, and 490 nm absorption bands for each glass, computing their respective oscillator strengths from equation (3), and least-squares fitting these to equation (4). These transitions were chosen because, unlike the 1530 nm transition, they do not have a magnetic dipole contribution (i.e., $f_{md} = 0$). Table I shows the resulting experimental and theoretical oscillator strengths for the ESA transition. Good agreement was obtained between measured and calculated values for both glasses.

Having measured the emission and ESA spectra, we estimated the uniform upconversion rate for our glasses as follows. Uniform upconversion at 1.5 μm in erbium is represented theoretically [1] by a $-C(N_2)^2$ term in the rate equation for the excited

population, N_2 , where C is the uniform upconversion constant. We can relate this constant to the spectral overlap between emission and ESA cross sections by applying Dexter's principles of energy transfer [6] in the *kinetic limit* [2] of high erbium concentrations. In this limit, the erbium ions are separated by a minimum distance, R_0 , and the energy transfer rate between erbium ions is very fast. Under these conditions, it can be shown [2,6] that

$$C \approx \frac{4c}{(2\pi)^3 n^2 R_0^3} \int \sigma_{em}(\lambda) \sigma_{esa}(\lambda) d\lambda \quad 5$$

where c is the speed of light and n is the index of refraction. Table I shows the calculated upconversion constants obtained from equation (5) using the measured spectra and assuming $n=1.5$ and $R_0=0.35$ nm. The latter value was taken as the Er-Er distance in crystalline Er_2O_3 [10]. These values yielded upconversion constants of 2×10^{-18} cm^3/s for glass A and 10×10^{-18} cm^3/s for glass B. The error in the overlap integral was estimated to be less than 20%. Using these results, we estimated the energy transfer lifetime, τ_{uc} , as $\tau_{uc} \approx 1/(CN_c)$, where N_c is the maximum erbium concentration defined as $N_c \equiv [(4\pi/3)R_0^3]^{-1}$. The calculated lifetimes, shown in table I, are consistent with values reported elsewhere [1].

Finally, since uniform upconversion is characterized by a decrease in the lifetime of the metastable level, ${}^4I_{13/2}$, with

increasing inversion [3], we attempted to verify the higher upconversion rate in glass B by comparing its lifetime behavior versus pump power to that of glass A. However, glass B exhibited anomalously higher upconversion rates than those predicted by our calculations. We suspect this behavior is due to inhomogeneities in the glass (i.e., phase separation) which yield an effectively higher erbium concentration [11].

In conclusion, we have accurately resolved, for the first time, the 1.7 μm ESA spectrum in erbium-doped glasses, which together with the emission spectra, define the 1.5 μm upconversion process in erbium. The measured oscillator strengths for the ESA transition are in close agreement with those obtained from Judd-Ofelt calculations. Using the measured spectra, we have estimated the upconversion rate in the glasses by computing the spectral overlap between the measured ESA and emission cross sections. The calculations yield upconversion constants in the $1-10 \times 10^{-18}$ cm^3/s range, which are consistent with upconversion effects reported in the literature [3,4] for other silicate glasses. Thus, this technique could be applied to help identify the glass hosts where uniform upconversion is minimized. In the presence of inhomogeneities, however, the glass may exhibit much higher upconversion rates than those predicted by these calculations.

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Figure Captions

Figure 1. ESA measurement apparatus.

Figure 2. Gain spectrum for an Er-doped barium silicate waveguide.

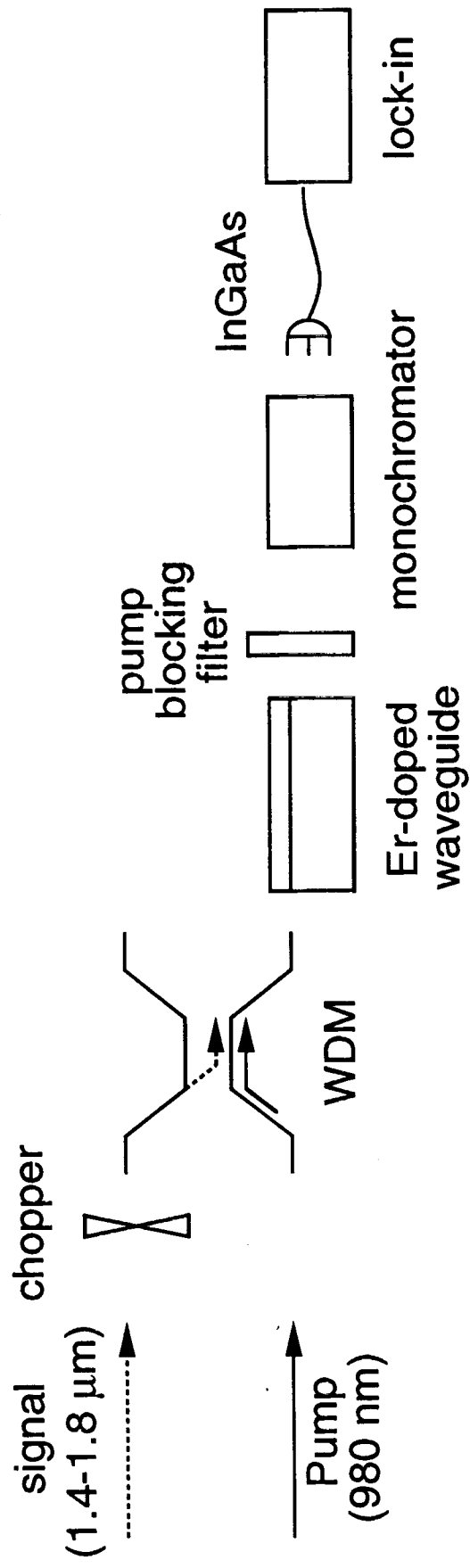
Figure 3. Measured emission and ESA spectra for Er-doped barium silicate glass.

Figure 4. Measured emission and ESA spectra for Er-doped alumino-phosphosilicate glass.

Glass	Cross Section		Oscillator		Upconversion	
	(10 ⁻²¹ cm ²)		Strength (10 ⁻⁶)		Rate	Lifetime
	⁴ I _{13/2} - ⁴ I _{15/2}	⁴ I _{13/2} - ⁴ I _{9/2}	<i>f</i> _{exp} ^{esa}	<i>f</i> _{JO} ^{esa}	<i>C</i> (cm ³ /s)	<i>τ</i> _{uc} (μs)
A	4.0	0.34	0.12	0.15	2x10 ⁻¹⁸	90
B	7.6	1.8	0.49	0.48	10x10 ⁻¹⁸	18

Table I Summary of results for Er-doped barium silicate (glass A) and alumino-phosphosilicate (glass B).

Fig. 1, J. Roman, Applied Physics Letters



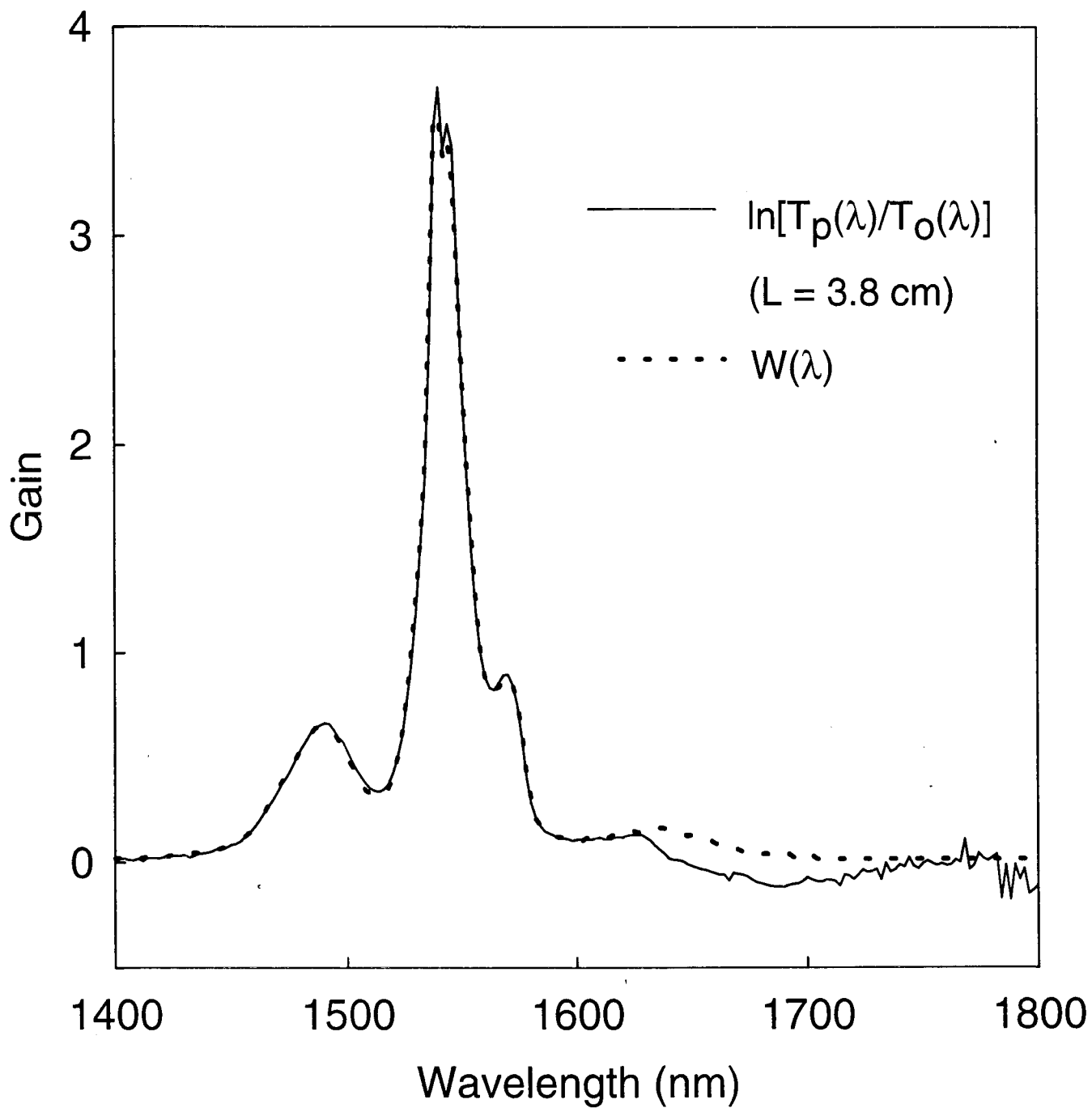


Fig. 2, J. Roman, Applied Physics Letters

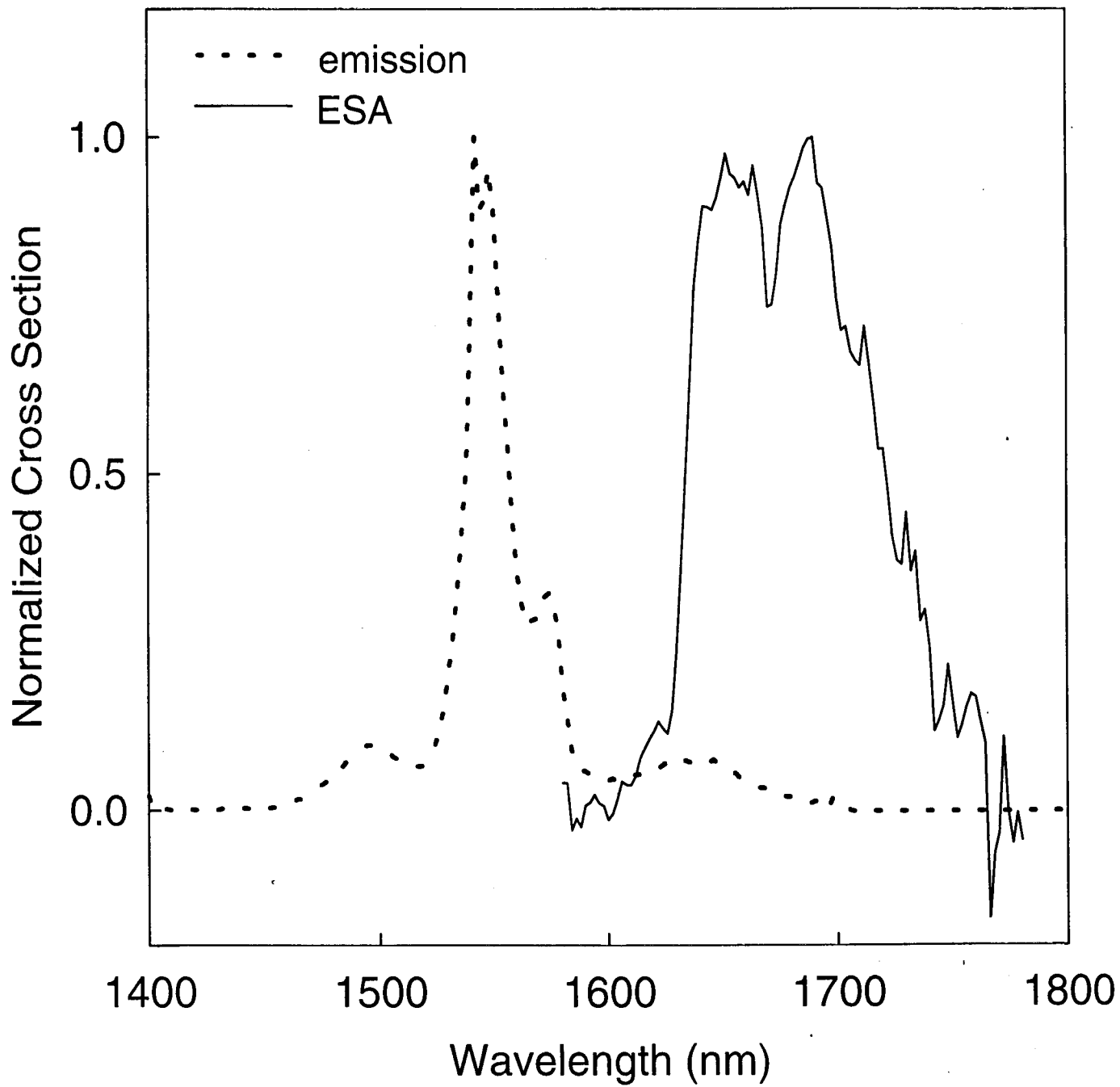


Fig. 3, J. Roman, Applied Physics Letters

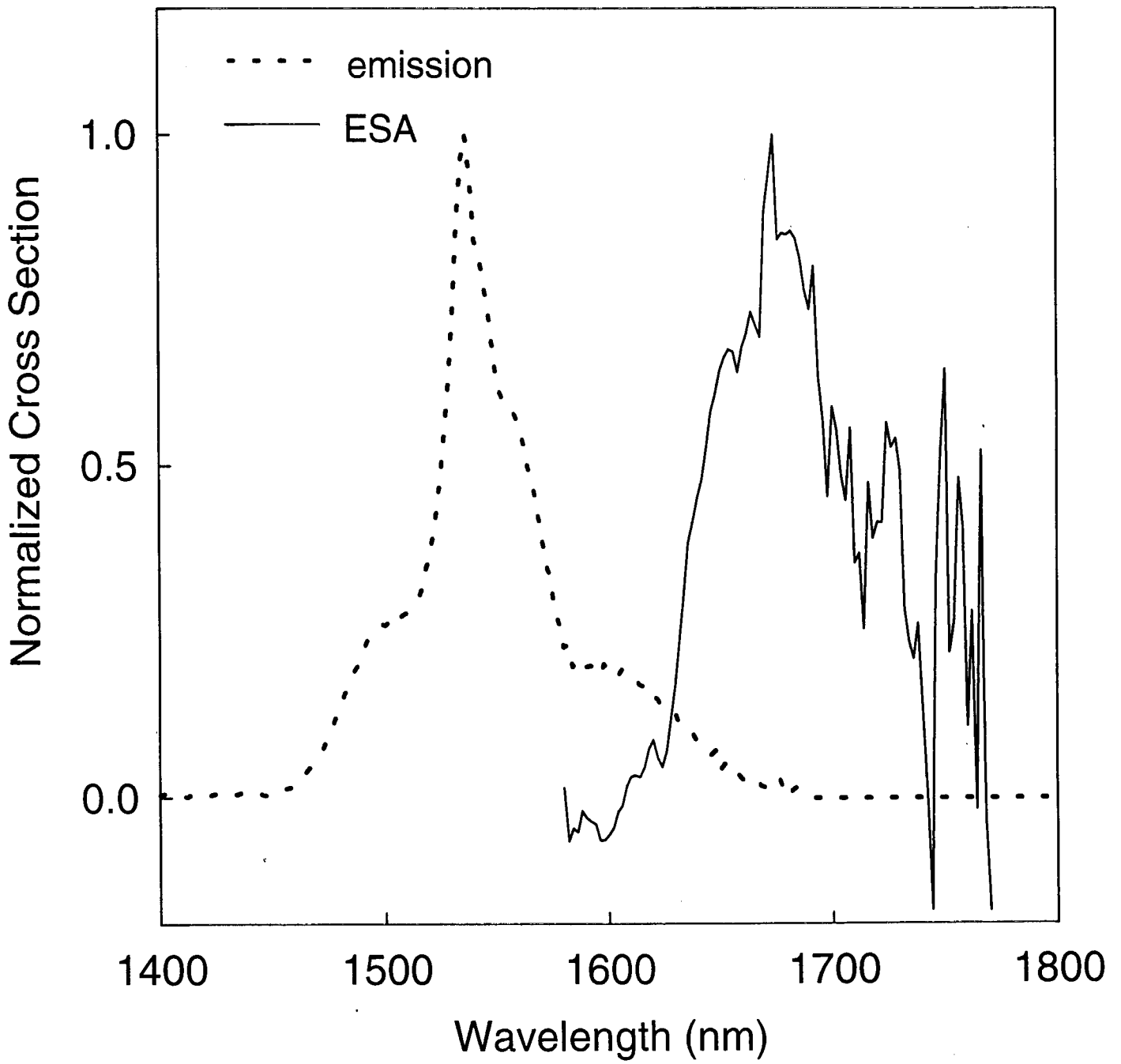


Fig. 4, J. Roman, Applied Physics Letters