Frequency-Domain Measurement of Spontaneous Emission Lifetime in Rare-Earth-Doped Gain Media

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Abstract: The spontaneous emission lifetime in Al_2O_3:Tm^{3+} waveguides is measured to be 568 ± 48 μs, using a frequency-domain method. The method is studied and verified in Er^{3+}-doped silica fiber, yielding a measured lifetime of 9.73 ± 0.08 ms.

OCIS codes: (160.5690) Rare-earth-doped materials; (160.4760) Optical properties; (120.3940) Metrology.

1. Introduction

The measurement of spontaneous emission lifetime is crucial for correctly modeling amplifier and laser behavior in many types of gain media. For longer lifetimes, the most common measurement method involves monitoring the emission or absorption with a chopped excitation, and characterizing the resulting decay signal. This method is limited by how well the transient system response can be resolved at low signal powers [1-3].

In contrast, the lifetime can be extracted more accurately from the transfer function between a sinusoidally varying excitation and the resulting absorption of an input signal [3]. The phase shift between the two signals can be precisely measured by modern electronics, allowing for lifetime measurements down to the picosecond range without the use of pulsed sources. In this paper, we show that with a sinusoidal pump modulation, the system bandwidth depends linearly on the steady-state pump rate. We then use this technique to verify and characterize the spontaneous emission lifetimes in Er^{3+}-doped silica fiber and Al_2O_3:Tm^{3+} waveguides.

2. Modeling the Transfer Function with a Modulated Pump

The population levels in a two-level system are dictated by rates of absorption by the ground state, and spontaneous and stimulated emission from the excited state. The rate of change of the ground state population is then given by

$$\frac{dn_0}{dt} = -\sigma_{sa}\phi_s n_0 + \sigma_{se}\phi_s n_1 - \sigma_{pa}\phi_p n_0 + \frac{n_1}{\tau} \tag{1}$$

where $n_{0,1}$ are the fraction of the species in the ground and excited states, $\phi_{s,p}$ are the continuous wave (CW) signal and pump rates, $\sigma_{sa,se,pa}$ are the absorption and emission cross-sections at the signal and pump wavelengths, and τ is the spontaneous emission lifetime of the excited state. Using a pump rate modulation where $\phi_p = \phi_{p0}(1 + m(t))$, and the steady-state ground state population of n_{0ss}, the transfer function between the modulation $m(t)$ and the change in the ground state population Δn_0 can be calculated as

$$H(s) = \frac{\Delta N_0(s)}{M(s)} = -\frac{\sigma_{pa}\phi_p n_{0ss}\tau_{eff}}{1+s\tau_{eff}} \tag{2}$$

Eq. (2) describes a low-pass filter with a cutoff frequency of $1/\tau_{eff} \approx \sigma_{pa}\phi_{p0} + 1/\tau$, given that $\phi_s \ll \phi_{p0}$ and $m(t)$ is small. The same filter response is also observed in the absorption of the input signal ϕ_s, as measured by a photodetector. Hence, the cutoff frequency scales linearly with the pump rate ϕ_{p0}. Moreover, the vertical intercept of the linear fit where $\phi_{p0} = 0$ yields the inverse of the spontaneous emission lifetime, $1/\tau$.

3. System Characterization and Lifetime Measurements

The measurement setup is shown in Fig. 1. The pump intensity is modulated by an external signal generator. Using a wavelength division multiplexer, the pump and signal are coupled to the device under test. The residual pump is then absorbed by a Si window before the photodetector where the signal power is recorded. A lock-in amplifier extracts the amplitude of the photodetector signal at the modulation frequency, and its phase difference from the modulation reference. The resulting transfer function is then used to obtain the spontaneous emission lifetime.

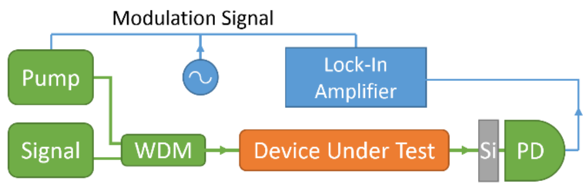

Fig. 1. Schematic diagram of the experimental setup used for the frequency-domain measurement.

The method is first verified by using a commercial Er^{3+}-doped silica fiber, with 980 nm pump and 1550 nm signal. Amplitude and phase responses for various pump powers are shown in Fig. 2(a) and (b). The measured filter characteristics reflect the predicted low-pass behavior. From the linear fit to the first pole frequencies in Fig. 2(c), τ is calculated to be 9.73 ± 0.08 ms, matching previously reported values for similar fibers [4].

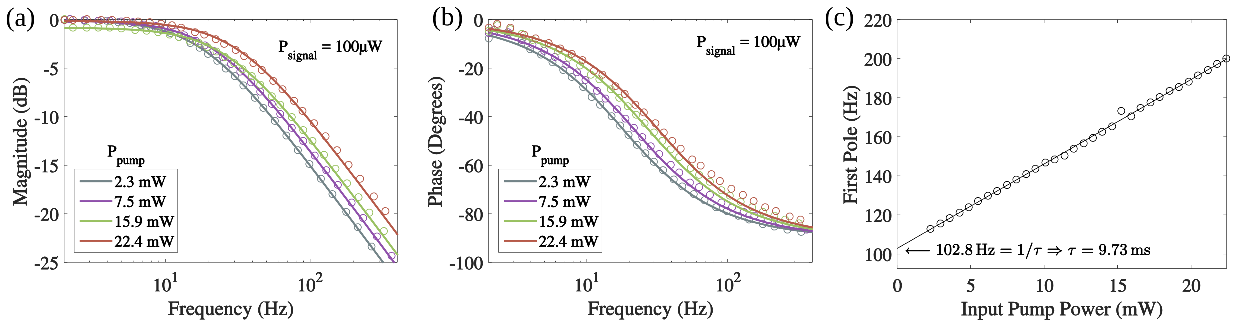

Fig. 2. (a) Amplitude and (b) phase responses of 1550 nm absorption in Er^{3+} doped silica fiber with respect to a modulated 980 nm pump. (c) Plot of first pole locations of the measured transfer functions, yielding a spontaneous emission lifetime of 9.73 ± 0.08 ms.

Next, the lifetime of Al_2O_3:Tm^{3+} waveguides were characterized. These 1 μm thick waveguides were fabricated using a reactive co-sputtering process [5] on top of 200 nm thick buried SiN segments. Using a 785 nm pump, and 1900 nm signal, the amplitude and phase responses were recorded as shown in Fig. 3(a) and (b), and matched to two-pole filter fits. The spontaneous emission lifetime was calculated to be 568 ± 48 μs [Fig. 3(c)]. The deflection of the phase from the single-pole response at frequencies over 1 kHz may be attributed to the existence of other population levels with lifetimes corresponding to these higher frequencies, as well as the lock-in amplifier's performance with decreasing input power.

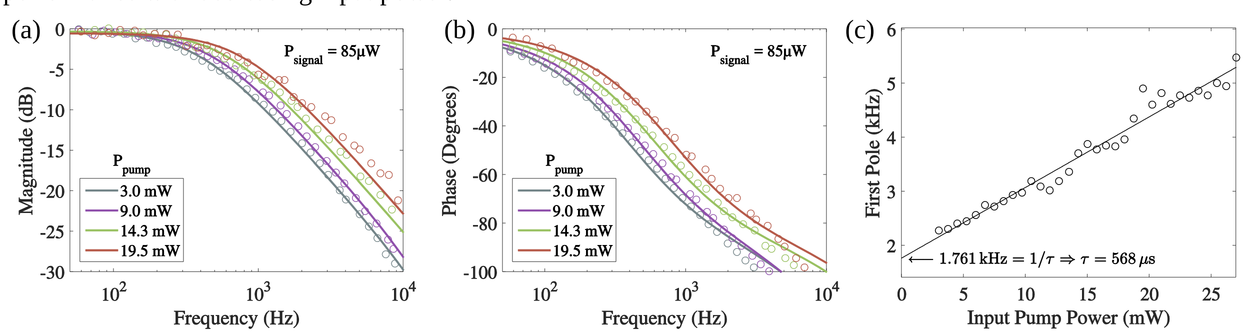

Fig. 3. (a) Amplitude and (b) phase responses of the 1900 nm absorption in Al_2O_3:Tm^{3+} waveguides with respect to a modulated 785 nm pump. (c) Plot of first pole locations of the measured transfer functions, yielding a spontaneous emission lifetime of 568 ± 48 μs.

In conclusion, we described a transfer function method for precisely determining the spontaneous emission lifetime using only frequency-domain techniques and CW sources. This method can be used in characterizing newly developed materials as well as measuring lifetimes that are too short to characterize without pulsed sources.

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4. References

[1] E. R. Taylor et al., "Spectroscopy of Tm^{3+}-doped Tellurite Glasses for 1470 nm Fiber Amplifier," *J Appl Phys* 92.1(2002): 112-117.
[2] J. Fick et al.,"High Photoluminescence in Erbium-Doped Chalcogenide Thin Films," *Journal of Non-crystalline Solids* 272.2 (2000): 200-208.
[3] J. Demas, *Excited State Lifetime Measurements* (Academic Press, 1983), Chap. 1-2.
[4] E. Delevaque et al., "Modeling of Pair-Induced Quenching in Erbium-Doped Silicate Fibers," *IEEE Photonics Tech Letters* 5.1 (1993): 73-75.
[5] E.S. Magden et al., "Fully CMOS-Compatible Integrated Distributed Feedback Laser with 250 ºC Fabricated Al_2O_3:Er^{3+} Gain Medium," CLEO: 2016 OSA Technical Digest, (Optical Society of America, 2016), paper SM1G.2