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SCALING THE RAMAN GAIN COEFFICIENT OF OPTICAL FIBERS
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Abstract Scaling rules for the Raman gain coefficient are provided with emphasis on the effective area and
wavelength dependence. Translation from measurements made at one pump wavelength to other pump
wavelengths is demonstrated.

Introduction
The Raman gain coefficient of an optical fiber is a critical parameter when designing Raman amplifiers
as it determines the magnitude and spectral shape of the gain for a given pump wavelength and power. It
is convenient to be able to predict the Raman gain coefficient for arbitrary pump wavelengths for different
types of fibers or apply measurements made at one pump wavelength to other pump wavelengths. Often
the Raman gain coefficient is assumed to scale inversely both with the pump wavelength and the
effective area of the fiber at the signal wavelength [1].

In this work, we discuss these assumptions and
present results that show the correct scaling, derived from a classical model for Raman scattering. We
then test these predictions using measurements of Raman gain spectra for several pump wavelengths.

Raman gain coefficient
The optical properties, such as the refractive index
and the Raman gain coefficient, of a light-guiding fiber
depend on the constituents of the fiber. Most
common fibers consist of a silica, SiO₂, host to which
germanium, GeO₂, is added in the core to increase
the refractive index.

The Raman effect originates from interactions
between optical phonons and the propagating electric
field. The phonons can be imagined as oscillations of
the oxygen atom in a Si-O-Si, Si-O-Ge, or Ge-O-Ge
bridge. The induced polarization of the molecule can
be expanded in terms of the displacement of the
oscillator. In this expansion, the permanent
polarizability is responsible for Rayleigh scattering,
whereas the differential polarizability is responsible
for Raman scattering [2].

The force that drives the oscillator originates from the
electric energy stored in the material. Thus by
applying a conventional model for a harmonic
oscillator, the amplitude of the oscillations can be
expressed through the induced polarization and the
electric field [3].

Combining the induced nonlinear polarization with the
amplitude of the oscillations, one may derive the wave equation for light propagating in a dielectric
material starting from Maxwell's equations. By
solving this wave equation, the gain coefficient due

where the subscripts x and p refer to the signal and
pump, α is the angular frequency, ni the effective
refractive index, R(r, ωs) the transverse part of the
electric field, c the velocity of light, and the integrals
are over the cross-sectional area of the fiber, A. Due
to space limitations, the complete derivation will be
shown elsewhere. Equation (1) shows theoretically
how the Raman gain coefficient scales with material
properties, wavelength, and modal overlap between
pump and signal.

Dependence on fiber-composition
Equation (1) also shows how the radial dependence
of χ(3) is taken into account when predicting the
Raman gain coefficient. In Ref. [4] we treated this by
decomposing χ(3) into a sum of contributions from
Si-O-Si and Si-O-Ge. For realistic germania
concentrations, Ge-O-Ge bridges are rare. The
relative distribution of Si-O-Si and Si-O-Ge bridges is
(1-2x):2x, where x is the GeO₂ concentration, which

Dependence on wavelength and effective area
In some cases the refractive index profile may not be
available but the spectrum of the Raman gain
coefficient of a specific fiber type may be known from
a single measurement at a specific pump wavelength.
The task is then to scale the spectrum of the Raman
gain coefficient to another pump-wavelength.

If the third-order susceptibility, χ(3) is assumed to be
constant over the entire fiber cross-section, Eq. (1)
reduces to

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\[ g_r(\omega_s, \omega_p) = \frac{3 \omega \ln \chi^2}{c^2 \varepsilon_0 n_p} A_{re}^{\omega_p}(\omega_p, \omega_s), \]

where \( A_{re}^{\omega_p} \) accounts for the radial overlap between pump and signal light,

\[
A_{re}^{\omega_p}(\omega_p, \omega_s) = \frac{\int |R| \, dA \int |R_p| \, dA}{\int |R| \, dA \int |R_p| \, dA},
\]

The conventional effective area, \( A_{ef}(\omega) \) is given by Eq. (3) with \( \omega = \omega_p = \omega_s \). Using the scaling shown in Eq. (2), the gain coefficient for new pump and signal frequencies \((\Omega_p, \Omega_s)\) is:

\[
g_r(\Omega_p, \Omega_s) = g_r(\omega_p, \omega_s) \frac{\Omega_p}{\omega_p} A_{re}^{\omega_p}(\omega_p, \omega_s) A_{re}^{\omega_p}(\omega_s, \omega_p).
\]

For relevant optical frequencies, \( \Omega_p, \omega_s, \sim \Omega_s, \omega_p \) and thus, for convenience, the ratio of pump frequencies is used rather than signal frequencies. To verify this scaling, we performed the following experiment. First, we measured the Raman gain coefficient of a non-zero dispersion shifted fiber (with a 55-\( \mu \)m\(^2\) effective area at 1550 nm) for four pump wavelengths: 1423.6 nm, 1443.8 nm, 1471.3 nm and 1496.0 nm. These measurements are shown in Fig. (1).

![Fig. 1: Measurements of Raman gain coefficient for four pump wavelengths.](image)

If we assume that the transverse part of the electric field is Gaussian, the effective area representing the overlap between pump and signal is as shown in Ref. [5], as:

\[ A_{re}^{\omega_p}(\omega_p, \omega_s) = \frac{A_{re}(\omega_p) + A_{re}(\omega_s)}{2}. \]

We used this assumption of Gaussian spatial modes to re-scale each of the Raman gain coefficients curves from their original pump wavelengths to a new pump wavelength of 1454 nm. \( A_{re} \) was calculated from the refractive index profile. Figure 2 shows the re-scaled coefficients versus the frequency difference between pump and signal, \( (\omega_p - \omega_s) \).

Starting from the measurements made for pump wavelengths that span 73 nm, we obtain a prediction of the Raman gain coefficient for the new pump wavelength that differ by only 4\%, confirming the validity of this approach.

![Fig. 2: Re-scaled Raman gain coefficients versus frequency difference between pump and signal for a 1454-nm pump.](image)

This example also demonstrates that the reduction in Raman efficiency with increasing pump wavelength is due in part by the reduced spatial overlap between the pump and signal modes. The difference between the peak Raman gain coefficients for 1423.6 nm and 1496 nm pumps is approximately 15\%, which can only be partially accounted for by the 5\% reduction in \( \omega_p \). Hence, to fully explain the reduced Raman efficiency one must take into account the reduced overlap of pump and signal with increasing pump wavelength.

**Conclusion**

In this work we have demonstrated how the Raman gain coefficient scales with fiber design and pump wavelength, with emphasis on the scaling with effective area and pump wavelength. In one example, the Raman gain coefficient decreases 10\%, when the pump wavelength increases 73 nm. It is demonstrated that a Raman gain coefficient measurement may be accurately scaled to other pump wavelengths if the refractive index profile of the fiber or the effective area versus wavelength is known.

**References**


