Characterization of spectral hole depth in Tm^{3+}:YAG within the cryogenic temperature range*

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In this paper, spectral hole depth dependence on temperature below 10 K in Tm^{3+}:YAG crystal is investigated in detail. A novel model is proposed to analyze the temperature dependence on the spectral hole. By using the proposed model, we theoretically deduce the temperature dependence of spectral hole depth. The results are compared with experimental results and they are in good agreement. According to the theoretic results, the optimum temperature in experiment can be found.

Keywords: phonon process, spectral hole depth, spectral hole width, Tm^{3+}:YAG

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1. Introduction

A wide variety of applications such as radio frequency (RF) signal processing,[1,2] quantum computing and memory,[3,4] ultrasound-modulated optical tomography,[5,6] optical storage,[7] spectral interferometry metrology,[8] measurement of optical frequency stability,[9] laser frequency stabilization,[10] and ultraslow light research[11] have been realized on the basis of spectral hole burning technology. Compared with high bandwidth analog radio frequency signal processing, the optical approach presents a distinct advantage without the need of using a high bandwidth analog to digital converter.

In RF signal processing, spectral hole width (homogeneous linewidth)[1,7,11] and spectral hole depth[1,6] are key parameters limiting signal-to-noise ratio, sensitivity, dynamic range, and resolution. These parameters are significantly affected by temperature.[12–14]

A model about temperature dependence of spectral hole width has been proposed and verified.[13–15] Meanwhile an experiment on temperature dependence of hole depth has been performed.[16] However, the theoretical model on temperature dependence of spectral hole depth has not been reported yet.

In this paper, the temperature dependence of spectral hole depth in Tm^{3+}:YAG crystal within the cryogenic temperature range is investigated in detail. Based on the dominant line broadening mechanism at low temperature[12–14] and area theorem of spectral hole,[17] a model is proposed to describe the temperature dependence of hole depth. By using the proposed model, it is theoretically deduced that spectral hole depth almost keeps a constant below 2.2 K, and decreases approximately in an exponential manner with temperature increasing over 4.5 K. The connection part, in a temperature range of 2.2 K–4.5 K, is the composite effect of temperature-independent part $\Gamma(0)$ and temperature-dependent part $\Gamma_{\text{phonon}}(T)$, which have the comparable magnitudes. We perform the experimental demonstration in crystal Tm^{3+}:YAG within the cryogenic temperature range. Numerical simulation and experimental result are in good agreement. By employing the theoretic result, the optimum temperature can be found in the sense of experimental result performance and equipment investment.

2. Spectral hole burning and the model of spectral hole depth temperature dependence

In spectral hole burning (SHB) materials (such as YAG crystal doped with rare-earth ions), the resonant frequency of each ion is slightly shifted from its normal value due to microscopic inhomogeneities, matrix defects, and disorder in the crystal, which is known as inhomogeneous broadening (inhomogeneous profile), as shown in Fig. 1. The SHB is the process of addressing only a small spectral subset of ions in the inhomogeneous profile by illuminating the crystal with a monochromatic laser source. Only ions that are nearly resonant in frequency with the laser beam absorb the photons and are then excited from their ground states. As a consequence, the absorption at the laser frequency is reduced, yielding a spectral hole in the inhomogeneous profile. When another

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frequency-chirped laser with weak intensity addresses the inhomogeneous profile of crystal, the spectral hole is mapped into time-domain.[9] Spectral hole depth is defined as the peak of the spectral hole. Spectral hole width is defined as full width at half maximum of the spectral hole as shown in the inset of Fig. 1.

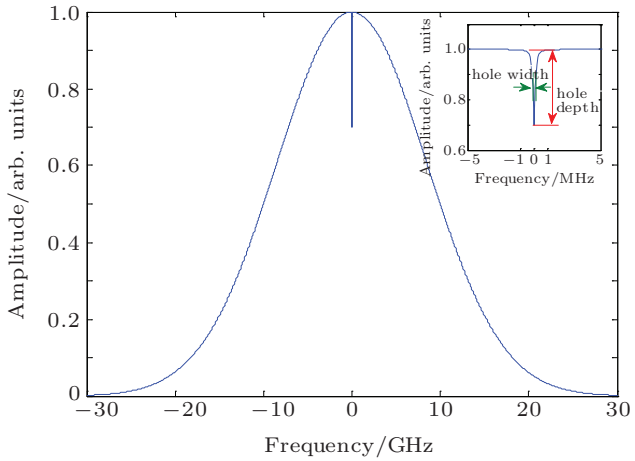


Fig. 1. (color online) Normalized inhomogeneous profile with an SHB at central position.

According to the area theorem of a spectral hole,[18] spectral hole area created by phonon process at low temperature is a constant (especially in trivalent rare-earth ions, such as Tm^{3+}), which can be described as follows:

$$D(T) \times \Gamma_{\text{hole}}(T) = C, \tag{1}$$

where $D(T)$ is spectral hole depth, $\Gamma_{\text{hole}}(T)$ the hole width, and C the constant.

In solids doped with rare-earth ions such as Tm^{3+} the spectral hole width $\Gamma_{\text{hole}}(T)$ can be written as[16]

$$\Gamma_{\text{hole}}(T) = \Gamma_{\text{pop}} + \Gamma_{\text{Tm-Tm}} + \Gamma_{\text{Tm-host}} + \Gamma_{\text{phonon}}(T). \tag{2}$$

The natural linewidth $\Gamma_{\text{pop}} = 1/(2\pi T_1)$ arises from the excited-state lifetime T_1. The term $\Gamma_{\text{Tm-Tm}}$ is due to Tm–Tm interaction. This term is a function of dopant concentration and laser intensity. The term $\Gamma_{\text{Tm-host}}$ arises from the interaction between the fluctuating spins of the host lattice. In the cryogenic temperature range, the above three terms are independent of temperature. Using McCumber and Sturge theory, temperature dependence of hole width is due to the term $\Gamma_{\text{phonon}}(T)$, which arises mainly from one- and two-phonon processes.[13] One-phonon process is the dominant spectral hole width broadening mechanism at cryogenic temperatures,[13,14,19] which is given by the formula:

$$\Gamma_{\text{phonon}}(T) = \frac{1}{\pi T_1} \exp\left(-\frac{\hbar\omega}{k_{\text{B}}T}\right), \tag{3}$$

where T_1 is the excited-state lifetime, $\hbar\omega$ the phonon energy, and k_{B} the Boltzmann constant.

The depth of spectral hole, $D(T)$, can be derived from Eqs. (1)–(3), and expressed as

$$D(T) = C/\left[\Gamma(0) + \frac{1}{\pi T_1} \exp\left(-\frac{\hbar\omega}{k_{\text{B}}T}\right)\right]. \tag{4}$$

To explain Eq. (4), take $C = 1$, $\hbar\omega = 27\ \text{cm}^{-1}$, and $\Gamma(0) = 8.86$ MHz for example (Fig. 2).

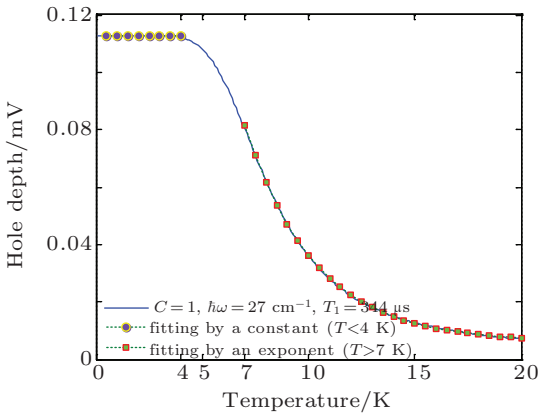


Fig. 2. (color online) Simulated temperature dependence of spectral hole depth ($C = 1$, $\hbar\omega = 27\ \text{cm}^{-1}$, and $\Gamma(0) = 8.86$ MHz), where the solid circles are fitted by a constant (adj. r-squared ~ 0.983), and the open squares are fitted by an exponent (adj. r-squared ~ 0.9997).

From Fig. 1, we see that the temperature dependence of spectral hole depth is divided into three parts by two turning points. In the temperature range of 0 K∼4 K, hole depth remains almost unchanged, which is due to the fact that $\Gamma(0)$ contributes more than $\Gamma_{\text{phonon}}(T)$ at low temperature. In the temperature range from 7 K to 20 K, hole depth decreases nearly exponentially with the increase of temperature due to the dominant effect of $\Gamma_{\text{phonon}}(T)$. Hole depth in the temperature range of 4 K∼7 K is the composite effect of $\Gamma(0)$ and $\Gamma_{\text{phonon}}(T)$, which have the comparable magnitudes.

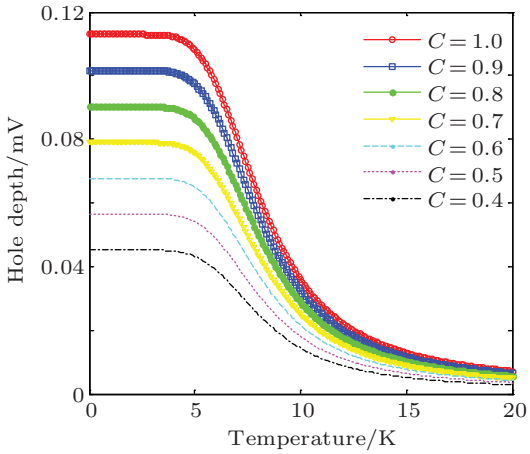


Fig. 3. (color online) Simulated temperature dependences of spectral hole depth C.

To study the effect of C on temperature dependence of spectral hole depth, we calculate the spectral hole depth from

Eq. (4), with C varied from 0.4 to 1 and $\hbar\omega$ set to be 27 cm^{-1}, in steps of 0.1, and the results are shown in Fig. 3.

From Fig. 3, we note that initial hole depth and the decrease rate are influenced by constant C.

To study the effect of $\hbar\omega$ on temperature dependence of spectral hole depth, we calculate the spectral hole depth from Eq. (4) with a series of $\hbar\omega$ ranging from 16 cm^{-1} to 28 cm^{-1} in steps of 2 cm^{-1}, with C being set to be 1, and the results are shown in Fig. 4.

It should be noted that the temperature of the turning point varies with phonon energy, i.e., the higher the phonon energy, the larger the turning point temperature is.

From Figs. 3 and 4, we know that constant C and phonon energy $\hbar\omega$ in Eq. (4) both contribute greatly to hole depth. Their values depend on crystal dopant concentration, type of matrix, laser intensity, etc. To simulate temperature dependence of hole depth, C and $\hbar\omega$ should be measured.

The experimental setup for the write/read process of spectral hole analysis in Tm^{3+}:YAG is shown in Fig. 5. The signal beam from a stabilized external cavity diode laser (NewFocus 6700), burns a hole at the write laser frequency into the crystal (Tm, 5 at%) inhomogeneous profile. One chirped read beam from the read source, which is controlled by a saw signal produced by AWG (Agilent 33250A), probes the inhomogeneous profile altered by the beam from the write source. Another frequency-chirped beam from the read source probes the unaltered inhomogeneous profile of crystal. The two read beams combine at the differential detector. A digitizing oscilloscope (Agilent 54833D MSO) records the spectral hole.

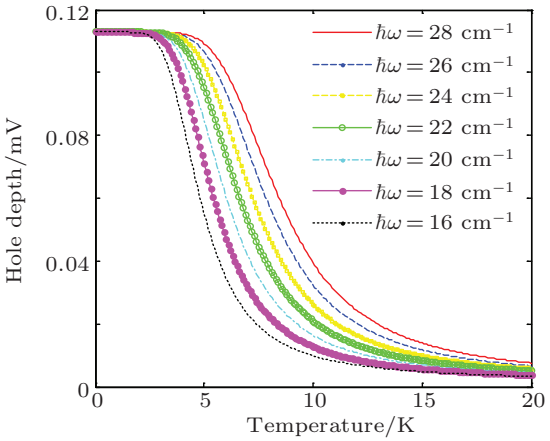


Fig. 4. (color online) Simulated temperature dependences of spectral hole depth of several phonon energies.

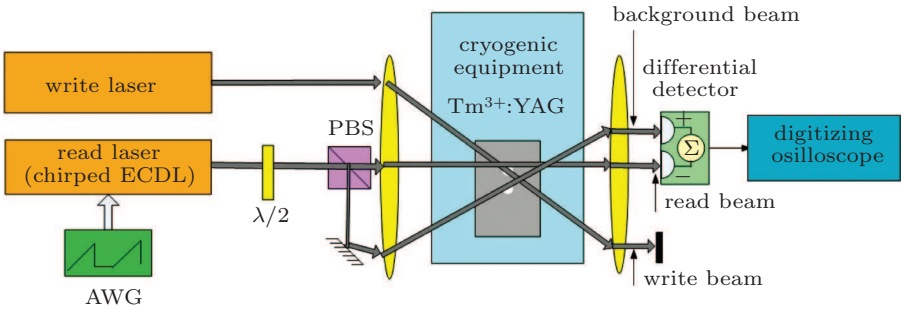


Fig. 5. (color online) Experimental setup. Write/read process for spectral hole analysis in SHB crystal. AWG stands for arbitrary waveform generator, PBS for polarizing beam splitters, ECDL for external cavity diode laser.

In the proof-of-concept experiment, write laser intensity is fixed at 2 mW/cm^2 emitting at a vacuum wavelength centred at 793 nm, corresponding to $^3H_6(0)$ and $^3H_4(0)$ of Tm element. The sample crystal is placed in a cryostat (OXFORD PT403, CP8300)). The temperature in the cryostat varies from 4.26 (limited by cryogenic equipment) to 8.6 K in steps of 0.2 K by using of liquid helium. The chirp band is 1-GHz wide and the spectral hole is burned at the center of the spectral band. Chirp rate is $\kappa = 0.1$ MHz/μs. The spectral features of the write laser are created on dozens of MHz-wide spectral band as shown in Fig. 6. The measured data of hole width and hole depth are shown in Table 1.

As expected, holes burned at higher temperature are broader, owing to phonon process, and therefore shallower.

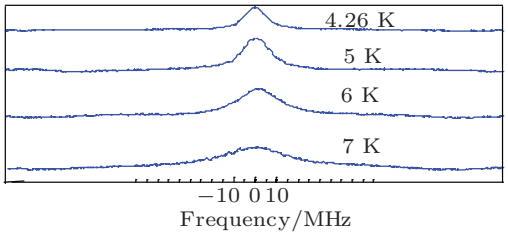


Fig. 6. (color online) Example of spectral holes burned in crystal at different temperatures.

The hole depth is plotted versus width from Eq. (1) as shown in Fig. 7.

Horizontal and longitudinal coordinates of each solid circle stand for hole width and depth respectively, which are measured in a series of temperatures. The dashed line fits to those solid circles by inverse proportional function (adj. r-squared is about 91%). The value of adj. r-squared about 0.91 shows

that area theorem of spectral hole is verified. The inset shows the magnified the dependence of the hole depth on hole width in a frequency interval between 10 MHz and 50 MHz. The fitting line by inverse proportional function illustrates that the product of width and depth approximates to a constant, whose value is 0.52.

Table 1. Temperature dependences of the measured spectral hole depth and width.

T/K	W/MHz	D/mV
4.26	11.12	0.038
4.4	11.22	0.043
4.6	11.89	0.041
4.8	13.51	0.039
5	13.35	0.036
5.2	15.56	0.037
5.4	16.07	0.037
5.6	17.33	0.034
5.8	19.95	0.033
6	21.13	0.031
6.2	22.56	0.026
6.4	23.70	0.025
6.6	25.99	0.023
6.8	27.66	0.018
7	28.95	0.021
7.2	33.00	0.018
7.4	35.7	0.019
7.6	33.00	0.014
7.8	34.00	0.013
8	37.09	0.015
8.2	38.65	0.013
8.4	37.45	0.012
8.6	48.00	0.011

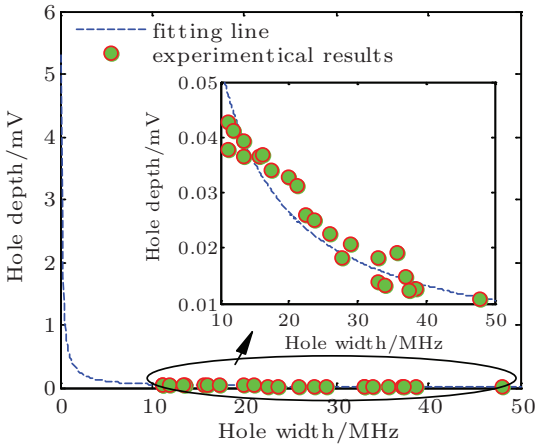


Fig. 7. (color online) Spectral hole depth dependence on spectral hole width.

The experimental result for the spectral hole width dependence on temperature is plotted in Fig. 8. The dashed line is fitted by Eq. (4). $\Gamma(0)$ is about 8.86 MHz, which can be observed from Fig. 8.

To calculate phonon energy, Eq.(3) is written as

$$\log[\pi T_1 \Gamma_{\text{phonon}}(T)] = -\frac{\hbar\omega}{k_{\text{B}}}\frac{1}{T}, \tag{5}$$

with $\Gamma(0) = 8.86$ MHz. Figure 9 shows the plot of $\log[\pi T_1 \Gamma_{\text{phonon}}(T)]$ versus $1/T$. The dashed line represents a linear fitting. The inset shows the magnified plot section in a range between 0.11 K^{-1} and 0.24 K^{-1}.

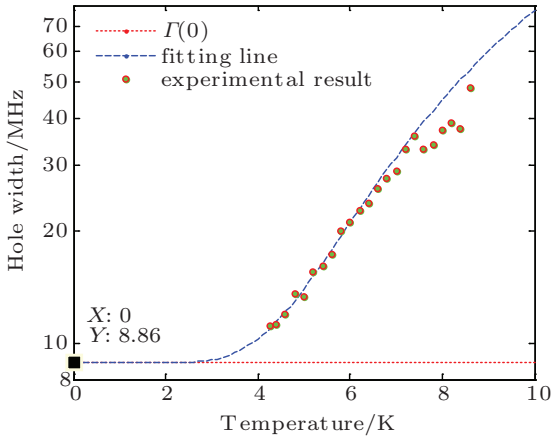


Fig. 8. (color online) Temperature dependence of spectral hole width.

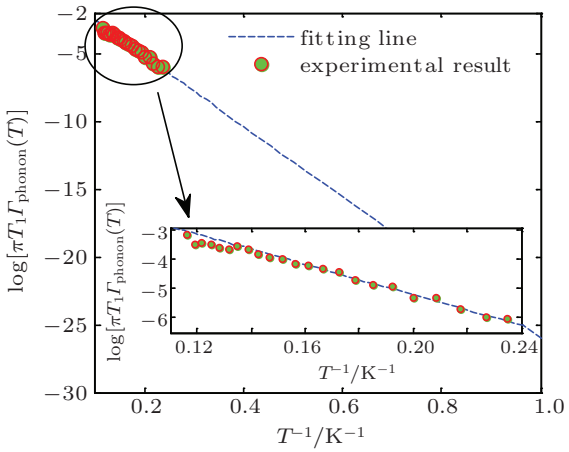


Fig. 9. (color online) Temperature-dependent hole width created by phonon process.

The fitting line by linear function shows that the one-phonon process is a dominant line boarding mechanism in the cryogenic temperature range.[13,14] The energy of one-phonon process is proportional to the slope, which is measured approximately to be 18 cm^{-1}. However, that value does not match the known 27 cm^{-1} splitting in the ground state $^3\text{H}_6$. The theory and the simulation in this paper are based on the assumption of perfect Tm^{3+}:YAG lattice and negligible phonon interferences. In reality, the imperfect lattice and phonon interferences all contribute to mismatch between theoretical result and experimental result.[20]

In Fig. 10, temperature dependence of spectral hole depth is shown, which can be simulated by using $C = 0.53$ and $\hbar\omega = 18$ cm^{-1}. The solid circles denote the experimental results.

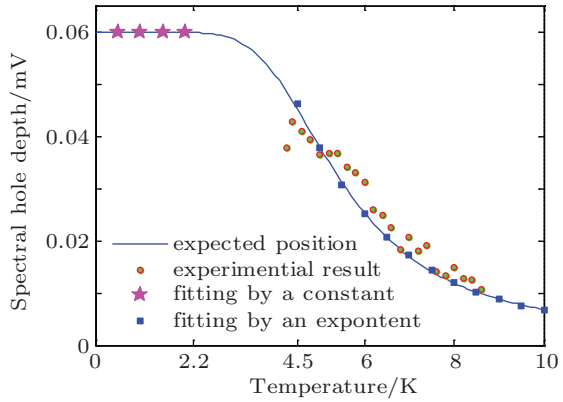


Fig. 10. (color online) Dependence of spectral hole depth on temperature.

From Fig. 10, we can see that the results are comparable to experimental results and they are in good agreement with each other. From the theoretical results, it can be found that the first temperature turning point is 2.2 K, and the second temperature turning point is 4.5 K. The first and third stages are shown by star symbols and solid squares respectively. Unfortunately, at the lower temperature (below 4.26 K) the measurement is not carried out due to the limitation of cryogenic equipment and at upper temperature (above 8.6 K) the measurement is not conducted either due to the hole depth being close to the threshold of detector noise which contributes to greater error.

3. Conclusion and discussion

In this paper, we experimentally verified that the one-phonon process at cryogenic temperatures is the dominant factor determining the hole width[11–13,17] and the spectral hole area is approximately conserved. Above all, we established a theoretical model to describe temperature dependence of spectral hole depth. By using the proposed model, we theoretically deduced the temperature dependence of the spectral hole depth. The theoretical results are in good agreement with experimental results. In theory, the lower the temperature, the better the performances of hole width and depth are. However, from the proposed model, we can notice that the "ceiling and floor effect" occur on depth and width when temperature decreases to a certain degree such as around 2.2 K in our experiment. Therefore, the optimum temperature can be found in the sense of experimental result performance and equipment investment.

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