Sideband generation using a Fiber-Optical Modulator (FOM)

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We have constructed a Fiber Optical Modulator (FOM), which produces on the incoming laser frequency shifts of the order of 30 GHz. The modulator consist of a fiber of sufficient length, where the transmission is saturated by stimulated Brillouin scattering (SBS). The frequency shift is determined by the parameters of the fiber and is fixed. The ratio of intensity of the shifted frequency and the incoming frequency can be varied over a large range by varying the incoming intensity with respect to the threshold intensity for SBS.

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Over the last 20 years molecular spectroscopy has benefited a lot from the use of single-mode, tunable lasers. Since the excitation rate can be large when using CW-lasers, experiments using two or more successive excitation steps are possible and reveal a lot of knowledge about the molecular structure. One new branch of molecular spectroscopy relies on the ability to cool and trap atoms and study these ultra-cold atoms while they are colliding with each other [1]. In this way long-range molecular states have been studied for the first time, where the internuclear distance is large (50-100 au). The ultra-cold temperature of the atoms suppresses the effects of Doppler broadening and allows spectroscopy with MHz-resolution.

The use of two or more excitations in one experiment puts a large demand on the available laser equipment. This is even more so when studying molecular spectroscopy of colliding, ultra-cold atoms, since the slowing, trapping and cooling of atoms also requires many different laser beams with several different frequencies. Techniques to generate sidebands on the frequency of a laser beam are therefore helpful. However, the present techniques like Acousto-Optic (AOM) and Electric-Optic modulators (EOM) only allow shifts in the order of 1-500 MHz and 1-10 GHz, respectively. Since molecular, vibrational structures are in most cases of the order of cm^{-1} ($\approx$ 30 GHz) or more, they are not useful in this respect.

We have developed a new modulator, the Fiber-Optical modulator (FOM), that allows us to generate a sideband on a laser beam with a frequency shift of $\approx$ 30 GHz. The technique utilizes Stimulated Brillouin Scattering (SBS) in a fiber. The theory of stimulated Brillouin scattering is discussed in many textbooks [2]. The incident light with frequency ω couples in the fiber to the phonons and induces density fluctuations in the fiber propagating at the sound velocity v_s. SBS light scattered off these density fluctuations in backwards direction will due to conservation of momentum be shifted to the red with a frequency

$$\omega_s = \frac{2nv_s}{c}\omega, \tag{1}$$

with n the refractive index. Light scattered in forward direction will not be shifted. The density fluctuations give rise to a variation in the permittivity ϵ proportional to the electrostrictive coefficient γ_e. This gives rise to an extra term in the polarization of the fiber, which then couples to the electric field.

The coupled wave equations for the intensity of the incident beam I_1 and the reflected beam I_2 are [2]

$$\begin{aligned} \frac{dI_1(z)}{dz} &= -g_B I_1(z) I_2(z) - \alpha I_1(z) \\ \frac{dI_2(z)}{dz} &= -g_B I_1(z) I_2(z) + \alpha I_2(z), \end{aligned} \tag{2}$$

where it is assumed that the incident wave travels in the positive and the reflected wave travels in the negative z-direction along the fiber. Here α is the absorption coefficient and g_B is the Brillouin gain coefficient for stimulated emission, which is given on resonance by

$$g_B = \frac{\omega^2(\gamma_e/\epsilon_0)^2}{2nv_s\Gamma_B c^3}, \tag{3}$$

with Γ_B the linewidth of the Brillouin gain.

If we neglect the absorption in the fiber ($\alpha = 0$) we can define $I = I_1 + I_2$ and $\Delta = I_1 - I_2$ and obtain

$$\begin{aligned} \frac{dI(z)}{dz} &= -2g_B I_1(z) I_2(z) = -\frac{g_B}{2}\left(I(z)^2 - \Delta(z)^2\right) \\ \frac{d\Delta(z)}{dz} &= 0. \end{aligned} \tag{4}$$

This implies that over the whole fiber the difference Δ between the incident intensity I_1 and the reflected intensity I_2 is constant. The wave equation for $I(z)$ can easily be solved and we obtain

$$\begin{aligned} I_1(z) &= \frac{\Delta I_0 \exp(g_B \Delta z)}{I_0\left(\exp(g_B\Delta z) - 1\right) + \Delta} \\ I_2(z) &= \frac{\Delta(I_0 - \Delta)}{I_0\left(\exp(g_B\Delta z) - 1\right) + \Delta} \end{aligned} \tag{5}$$

with I_0 the input intensity. The only constant to be determined is Δ. In Fig. 1 we have plotted the results for our fiber assuming a specific value for I_0 and Δ. We see that most of the incoming light is reflected back in the beginning of the fiber, until the intensity becomes below the threshold Δ, in which case the intensity remains constant until the end of the fiber. The transmitted light intensity is therefore equal to Δ. For the SBS light we see an exponential increase of the intensity from the end to the beginning of the fiber.

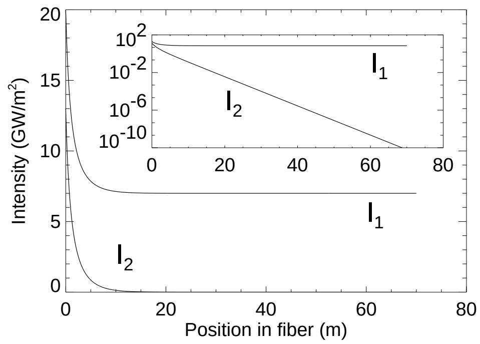

FIG. 1. Plot of the intensity of the incident (I_1) and reflected (I_2) light in the fiber as a function of the position z in the fiber. The incident intensity is 20 GW/cm^2, the threshold for SBS is 7 GW/cm^2 and the length of the fiber is 70 m. The inset shows the same plot on a logarithmic scale.

SBS becomes important in optical fibers, when spontaneously emitted light at the end of the fiber is sufficiently amplified during its travel through the fiber by stimulated emission. This normally occurs when the exponential amplification in Eq. 5 reaches a certain threshold [3], i.e. $g_B \Delta L \approx c_{th}$ with $c_{th} = 20 - 30$ and L the length of the fiber. From this one can derive the threshold for SBS as $\Delta_{th} = c_{th}/g_B L$. If I_0 is below Δ_{th} all light will be transmitted through the fiber. However, if we increase the intensity above Δ_{th} only a fraction Δ_{th} will be transmitted and a fraction $I_0 - \Delta_{th}$ will be reflected. This is the principle of our technique to generate a sideband. Note, that for our fiber (see Tab. I) we have $\Delta_{th} = 7 \times 10^9$ W/m^2, or $P_{th} = \Delta_{th} A_e = 70$ mW.

In the previous discussion we have assumed that the stimulated emission of SBS light is triggered by spontaneously emitted Brillouin photons. However, the end facets of optical fibers are uncoated. A small part of the SBS light propagating to the beginning of the fiber will be reflected back into the fiber at the facet. Again at the end of the fiber a small part of this light will be reflected and this can serve as the initial SBS light. For this doubly reflected light we have $I_2(L) = r^2 I_2(0)$, with r the reflection coefficient at the facets. Assuming $I_0 \gg \Delta$ and strong amplification in the fiber we obtain from Eq. 5 $I_2(0) \approx \exp(g_B \Delta L) I_2(L)$. These two equations can only be consistent, if $r^2 \exp(g_B \Delta_{th} L) = 1$, or

$$\Delta_{th} = \frac{-\log(r^2)}{g_B L}. \tag{6}$$

For our fiber we have $r = 0.03477$, or $\log(r^2) = -6.72$. So due to the backscattering the threshold for SBS light is lowered by a factor 3-4.

Using the exact relation of Eq. 5 for I_2 we can no longer obtain an analytical expression for Δ. However, the threshold for the occurrence of SBS light will still be given by Eq. 6. For $I_0 < \Delta_{th}$ we have $\Delta = I_0$. For $I_0 > \Delta_{th}$ we still require a balance between the loss due to the reflections and gain due to the SBS process and we have the condition

$$I_0 \left(\exp(g_B \Delta L) - 1\right) = \Delta \left(\frac{1}{r^2} - 1\right), \tag{7}$$

which has to be solved numerically. However, it is evident from Eq. 7, that an increase in I_0 must be accompanied by a decrease in Δ. Thus for increasing input intensity we expect a decrease in the transmitted intensity.

For the sideband generation we used 70 m of single-mode, polarization preserving optical fiber (York HB600, see Tab. I). The fiber has been cleaved on both ends to obtain perfectly flat end facets. The facets are not anti-reflection coated and have an intensity reflection coefficient r=3.47% for both the incoming and outgoing light. The incoming laser light is generated by a CW single-mode ring dye laser operating on Rhodamine 6G at a wavelength of 590.0 nm and the maximum available power is approximately 250 mW. After passing through an optical isolator the laser light is focussed on the facet of the fiber with a microscope objective with an incoupling efficiency η.

The intensities of the transmitted and reflected light are measured with calibrated photodiodes and the results are shown in Fig. 2. At low input intensities both transmission and reflection are linearly dependent on the input intensity, where the intensity of the transmitted light is given by $I_t = \eta(1-r)^2 I_0$ and the intensity of the reflected light is given by $I_r = r I_0$. However, at higher input intensities we observe that the transmission saturates. At the same time we observe an increase in intensity of reflected light. To study the strong increase in reflected light we analyzed the reflected signal by leading a small fraction through a Fabry-Perot interferometer. Below saturation we only observe the peak of the incoming frequency component. However, above saturation we observe a second peak, which increases strongly above saturation. From the relative signal strengths of the two components we could split the intensity of the reflected light into two contributions, directly reflected light and SBS light, and plotted the result in Fig. 2.

TABLE I. Parameters of the fiber used (York HB 600).

parameter	symbol	value
refractive index	n	1.45843
reflection coefficient	r	0.03477
velocity of sound	v_s	5760 m/s
effective core area	A_e	10.2 μm^2
attenuation		11.4 dB/km
fiber length	L	70 m
Brillouin gain coefficient	g_B	5.17×10^{-11} m/W
Brillouin gain width	Γ_B	85 MHz

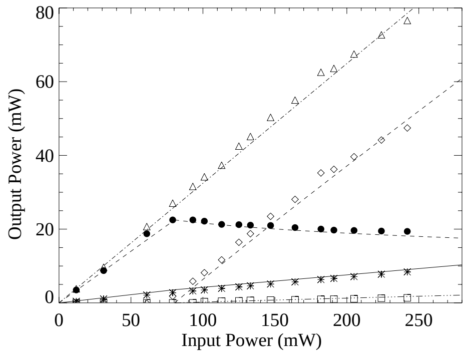

FIG. 2. Power of the transmitted and reflected light as a function of the input power. (•) Transmission of incoming light, (□) transmission of SBS light, (⋆) reflection of incoming light, (◇) reflection of SBS light, and (△) total power. The dashed and dotted lines are calculated from the model discussed in the text using $\eta = 29\%$. We assumed in the model that the effective core diameter is 23% larger than the value quoted in Tab. I.

From Fig. 2 we determine that the onset of saturation and therefore also the threshold for SBS occurs at $P_{th} = 22.5$ mW. From Eq. 6 we find $\Delta_{th} = 1.85 \times 10^9$ W/m^2, or $P_{th} = I_0 A_e = 18.9$ mW, which corresponds very well with the experimentally observed threshold. The agreement between model and experiment clearly indicates that the internal reflection of the SBS light in the fiber is the seed for the SBS amplification, since spontaneous emitted SBS light would require a threshold which is a factor 3-4 higher, which is clearly in disagreement with our experimental result.

To further support our model we have numerically solved Eq. 7 and plotted the results for transmission and reflection in Fig. 2. The agreement between model and experiment is very good. Even the decrease of the transmitted intensity for increasing intensity above saturation is reproduced in the model. This effect can be understood as follows: The threshold is determined by a balance between the loss due to transmission at the end facets of the fiber and the gain due to the amplification in the fiber. The loss coefficient is independent of the input intensity. Increasing the input intensity increases the intensity in the first part of the fiber most strongly. The amplification of the SBS light in the first part is therefore strongly enhanced, which requires less amplification in the last part. The threshold will therefore be lowered.

For the determination of the frequency shift (ω_s) of the SBS light we led the transmitted and reflected light through a number of spectrum analyzers having different Free Spectral Ranges (FSR). Typical scans observed with a 1.494 GHz FSR spectrum analyzer are displayed in Fig. 3. From the measurements we obtained a Brillouin shift $\omega_s/2\pi = 28.54(3)$ GHz. This is close to the Brillouin shift calculated from Eq. 1, which yields $\omega_s/2\pi = 28.48$ GHz. For the determination of the spectral width of the SBS light the resolution of the spectrum analyzer ($\Delta\omega/2\pi \approx 30$ MHz) is insufficient. We measured the spectral distribution of the SBS light from the beat signal with light of a second dye laser and performed the same analysis with the original laser light. We found that both spectral widths are in the order of 1 MHz. So no apparent broadening of the SBS light occured due to the SBS process. In our spectroscopic experiment [4] the observed structures have widths of the order of 10 MHz and are clearly resolved in the data, which is another indication that the width of the SBS component is well below 10 MHz.

Since most of the reflected light is shifted one could change its polarization and study molecular states using two different polarizations for the two excitation steps. Changing the frequency shift could be practical, however, that is not easily done, since neither the index of refraction nor the velocity of sound in the fiber can be changed easily. One of the possibilities to create larger shifts would be to inject the reflected SBS light into another fiber and create a doubly shifted frequency. This procedure, however, cannot be repeated many times, since the incoupling causes losses and each time we need sufficient power to saturate the fiber. Still, the device is very simple to construct and can serve as a simple frequency shifter in many other experiments as well.

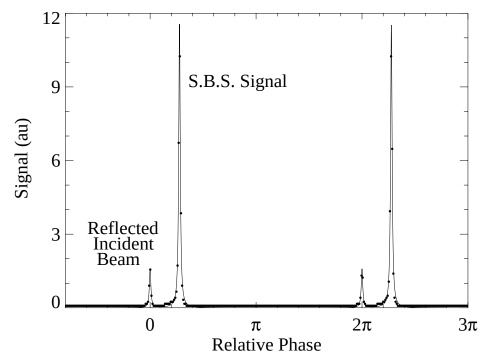

FIG. 3. Spectrum of the reflected light measured by a 1.494 GHz FSR analyzer. The solid line represents a fit through the data, including the spectrum analyzers transmission function and the frequency shift of the SBS light.

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