Some Study of Fiber Optic Communication for High Frequency Optical Pulse

Chakradhar Rajowar

Assistant Professor, Dept. of Physics, Bankura Sammilani College

Abstract

Intense trains of single-femtosecond pulses can be generated using MRG, a nonlinear technique. Single-femtosecond pulses can be generated using a wide range of Raman orders, from near-infrared (near-IR) to ultraviolet (UV). This technique, despite its lack of pulse duration, is able to increase pulse power due to the small frequency spacing between different Raman orders, which increases temporal spacing between the pulses. Nonlinear optics applications requiring intense but brief laser pulses can benefit greatly from the use of MRG.

Keyword: MRG, Pulses, Fiber Optics, Laser.

1. Introduction

Today's technology is based on the accuracy of our measurements. As we make more progress in many different areas, we need to have a better understanding of the superfast processes. Ultrafast optics provides us the tool to increase our temporal resolution. These days, ultra-short laser pulses have many different applications in different areas such as ultrafast spectroscopy, laser-controlled chemistry, frequency metrology, optical communication, materials processing, biomedical application, etc. These applications have one thing in common, and that is a short burst of light. After the invention of lasers, many different methods have been invented to create short laser pulses. Q-switching, mode-locking, high order harmonic generation (HHG), and multi frequency Raman generation (MRG) are different methods to create short lasers pulses with different pulse duration and energy.

Methods to Create Short Laser Pulses

Q-Switching

One of the first methods that have been used to create short laser pulses is Q-switching method. The word 'Q' comes from 'quality factor', which plays a crucial role in designing any laser resonator. Q factor in laser physics is related to the loss inside a resonator. Basically, the resonators with high Q-factors are highly desirable. To generate short laser

pulses, we can suddenly change the Q factor of a laser cavity by an active or passive device. By changing the Q factor, we are changing the loss inside the resonator. So, how does this loss make a short laser pulse?

In a lasing CW laser, the gain is always higher than the loss. Atoms are pumped up continuously to higher states, and thereafter by having stimulated emission, they will come to a lower state. Then, we have steady output power. In the Q-switching, we create a temporary loss inside our system. This means that we stop atoms having the stimulated emission. The atoms will be pumped to the higher states, but they cannot come to the lower state because we have created the loss in the system. Suddenly the loss of the system will be changed, and all the atoms come to lower state. Finally, we have a powerful short pulse. This is the basic mechanism of Q- switching. By creating the loss, or in other words, by changing the Q factor of the resonator, we can have a short laser pulse with high intensity. This changing of the loss inside the resonator can be done by putting active loss modulators (acoustic optical modulators or RF modulators) or passive modulators (saturable absorber) inside the cavity of a laser. The duration of output pulses will be a function of two factors. The first one is the lifetime of the atoms at higher state, which strongly depends on the laser gain medium. The second one is how fast we can change the loss of our system. Usually, the output pulse can have a pulse duration of a few micro seconds to tens of picoseconds with the energy of tens of mJ in each pulse. In the Q-switching, the pulse duration is always longer than the roundtrip time, and repetition rate can be varied from a few hertz to a few Megahertz.

Q-switching is an excellent method to create powerful short laser pulses. But if ultra-short laser pulses are needed, we need to use other techniques.

Mode Locking

Another technique to create ultra-short laser pulses is mode locking. The mode-locking is based on constructive interference between different axial modes inside a laser cavity. Mode-locked lasers usually can generate pulses in picosecond to femtosecond regime. The energy in each pulse can be between micro joules to nano joules, and the repetition rate of these oscillators can be between Megahertz to Gigahertz.

To generate short laser pulses, we need to use a loss modulator in the laser resonator. The loss modulator should create a periodic loss which is matched to the roundtrip of the cavity. By doing this, the energy will be transferred to the longitudinal modes of our cavity, and the

relative phase between the longitudinal modes will not change. In other words, the phase will be locked. Then constructive interference can make an ultra-short laser pulse.

Just like Q-switching, the mode-locking methods can be divided into two groups: active and passive. In the active mode-locking, an electronic loss modulator is responsible for creation of a periodic loss. However, in the passive mode-locking a saturable absorber creates the loss. This absorber creates a high loss for low-intensity pulses. It allows only the pulses with high intensity to pass, and the recovery time of the saturable absorber should be lower than round trip time (because we want that one pulse to pass!). In a mode-locked laser, the pulse duration is always shorter than the roundtrip of the cavity, which will cause to have a pulse in the cavity at any moment. Moreover, the length of the cavity is the primary factor which determines the repetition rate of the oscillator.

Kerr lens mode-locking is another passive way to make ultra-short laser pulses. These days the Ti: sapphire oscillators based on this technique can make pulses as short as five femtoseconds. Kerr lens mode-locking (KLM) is based on Kerr effect. This effect is a nonlinear effect which can lead to changing of the refractive index of the medium. This change in refractive index will cause the medium to work as a lens for ultra-short laser pulses, which is called self-focusing. This self-focusing effect causes the material to works as saturable absorber, which eventually makes a periodic loss in the system. This effect is the basis of the Kerr lens mode-locking, which many these days' oscillators uses this principle to generate ultra-short laser pulses. Ti: sapphire crystal has a high nonlinearity and also a broad gain bandwidth. These two factors make this crystal the best candidate for generation of ultra-short laser pulses by Kerr lens mode locking technique.

High Harmonic Generation

The main limitation to creating shorter laser pulses is the central frequency of a carrier wave. This central frequency will determine the temporal resolution of a pulse, which is the duration of one single optical cycle. This limitation explains why Ti: sapphire oscillators cannot make pulses shorter than five femtoseconds. To push the boundaries of ultrafast optics, we need to move to shorter wavelengths, and high harmonics generation (HHG) is one of the widely used ways to reach XUV and soft X-rays.

HHG can happen by focusing a very intense laser pulse into some specific gas (usually monoatomic gas like Neon or Argon). After that, the gas molecules will modulate the frequency of incident laser beam and generate odd harmonics of the incident beam. These

harmonics can easily reach soft X-ray. This harmonic generation is a coherent process wherein these harmonics are highly correlated to each other. By correcting the phase of these harmonics it is possible to generate attosecond pulses. The world's shortest pulse generated by HHG up to date is 43 attosecond. HHG, however has a big drawback namely efficiency. This means that HHG cannot be used in many applications which need powerful pulses, and the output of HHG cannot be used for nonlinear experiments.

Multi Frequency Raman Generation

Multi frequency Raman generation (MRG) is a nonlinear technique to create single femtosecond laser pulses. The temporal resolution of this technique is not comparable with HHG, but the energy of each pulse can be high (mJs), which will enable us to use MRG in areas that need intense pulses.

Just like the other short laser pulse generation methods, MRG also needs a broad spectrum. In the MRG, different Raman orders of a specific medium will be used to make a frequency comb from near IR to UV. This broad spectrum will enable us to create intense single-femtosecond pulses. The efficiency of MRG is much higher than HHG's, making MRG the best choice for applications that need intense short laser pulses.

MRG can be achieved by pumping a Raman medium using two powerful pumps coupled to the Raman transition of a specific medium. Stimulated Raman Theory can describe the process. The Raman medium can modulate the incident frequency and scatter the Stokes and anti-Stokes orders 5. This process can happen over and over again. These scattered orders can cover a broad spectrum.

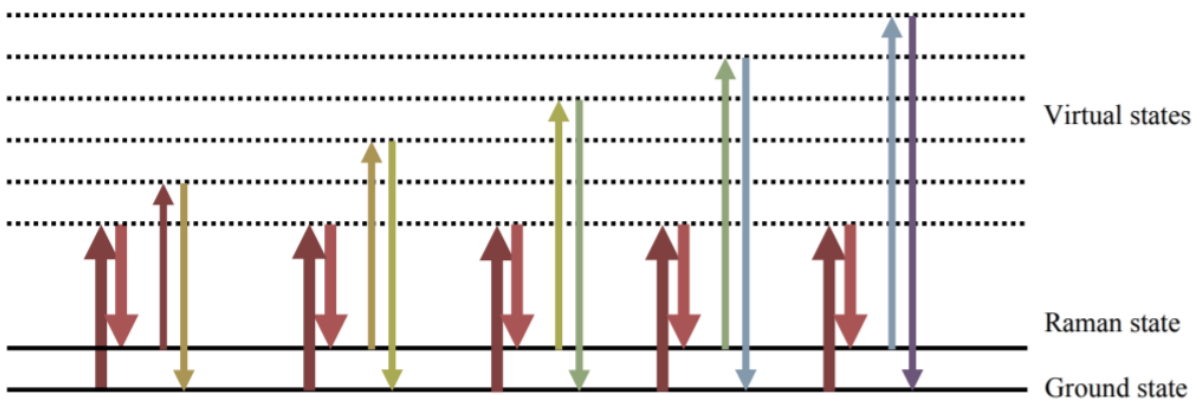

Figure 1. Energy level diagram for MRG

When the pumps intensity becomes sufficient, MRG can cover a broad spectrum

2. Pulse Compression Using Multiple Raman Orders

After the 90s, by using MRG, different techniques have been developed to create 1fs pulses. A good example of that has been done by Kung and his group (H. Chan, 2011). They have used 2 nanosecond pulses of frequency ω_0 and $2\omega_0$, which were coupled to Raman state of H_2 molecules. This resulted in different phase locked Raman orders, which made a frequency comb. In this study, they used four prisms and one phase modulator to generate pulses as short as 850as.

Practically, MRG can be studied in three different temporal regimes. These regimes can be understood by comparing the dephasing time of the molecules (T_d) to the duration of the pump pulses (T_p). Dephasing time of the molecules is a function of the molecular collisions, which cause atoms not to act coherently. In the adiabatic regimes, the pumps' duration is longer than the dephasing time ($T_p > T_d$). In the transient regime the dephasing time and pumps' durations are the same ($T_p \approx T_d$), however in the impulsive regime, the pumps duration is smaller than the dephasing time ($T_p < T_d$). A great review generation of ultra-short laser pulses by using Raman excitation has been written by Baker and his colleagues (S. Baker, 2011). Further, the most important experiments in this field will be explained.

Harris and Sokolov have theoretically studied the MRG in the adiabatic regime. The most important result of their theory is that the Raman orders can be phased. It means that the relative phase between the orders will not change. Then, by adding the orders together and temporally overlapping them, it is possible to make short laser pulses. They have also experimentally conducted an experiment to generate short laser pulses in the adiabatic regime. They used a four prism delay line and a liquid crystal phase modulator to time the seven Raman orders, which were spanning from the 1.56 μm to 410 nm. After timing all the seven orders, they generated pulses with the temporal duration of 1.6 fs, pulse separation of 11 fs, and the peak power of 1 MW (M. Katsuragawa, 2005). Katsuragawa and his group used a dual-wavelength injection-locked Ti: sapphire laser and liquid N2 as the Raman active medium to adiabatically generate Raman orders. Finally, they used a setup base on chirp mirrors to time up all the Raman orders and generate pulses with the duration of 20 fs, repetition rate of 10.6 THz, and peak-power of 2 MW. The main drawback in the adiabatic regime is the low peak power of the generated pulses. Since, the repetition rate in this regime is 7 very high, the result is the pulses have low peak power, which eventually makes this technique not suitable for nonlinear experiments.

In order to have MRG in the impulsive regime we need to use pump pulses with the duration of a few-femtoseconds. Theoretical works and simulations have showed that in this regime it is possible to generate a broad spectrum to produce half-cycle-pulses. But in practice, it has been shown that self phase modulation will happen and compete with Raman process, therefore, decreasing the efficiency of Raman generation. In order to avoid this problem, we can use another pulse with lower energy and delay. This can increase the efficiency of Raman generation without having self phase modulation (A. Nazarkin, 2002). It has been predicted that this technique can generate spectrum, which is sufficient for producing 1fs pulses. Also by changing the injection time of the probe pulse, it is possible to be sure of arriving in phase, hence, causing to have good pulse compression (V. Kalosha, 2002).

According to previous studies, researchers have shown that it is possible to generate 3.8fs pulses by exciting the Raman state of SF6 gas.Researchers have also showed that generating 23fs pulses is possible by using N2 as Raman active medium (F. Noack, 2005). The next studies in impulsive regime needs to generate wider spectrum. But because of the nonlinear interactions, this generation cannot be simply done by increasing the energy of the input pump pulses.

Comparing to transient and adiabatic regime impulsive MRG is not suitable for generating ultrashort laser pulses. The main reason is that in this regime the interaction between the SPM and the MRG will affect the final output spectrum. Also, as previously mentioned, it is not possible to generate pulses with high peak power in the adiabatic regime.

The next regime for studying MRG is transient regime. MRG in the transit regime was first observed by Irie and Imasaka through using the H_2 as the Raman active medium and a UV excimer laser as a single pump. Sali and his colleagues has also shown that by using two color pumping in the transient regime, it is possible to generate a wide spectrum in both H_2 and CH_4 (E. Sali, 2004).

3. Description of Short Laser Pulses

In order to describe a short laser pulse, let us first start by describing a plane monochromatic wave. We have the Maxwell wave equation:

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c}\frac{\partial^2 E}{\partial t^2} = 0$$

The solution for this equation is a plane monochromatic wave.

$$E(t,z) = E_0 e^{i(\omega_0 t - kz)} + cc$$

Equation 2 describe the nature of a plane wave, which has one frequency. In the real world there is not any source, which can produce monochromatic light waves. All of the light waves have a limited bandwidth, which does not allow them to be a single frequency. But, in many cases the bandwidth for a CW laser is negligible. For example, a typical He-Neon laser has the bandwidth of 0.002nm, which is very small and can be called monochromatic.

In order to describe a CW laser pulse, we also need to solve the Helmholtz equation, which is:

$$(\nabla^2 + k^2)E(x,y,z) = 0$$

The solution for equation 3, provides us the general representation of a Gaussian laser beam, which is:

$$E(x,y,z) = I_0 e^{[-\frac{x^2+y^2}{\omega^2(z)}]} e^{[-i\frac{k(x^2+y^2)}{2R(z)}]} e^{[-ikz-\varphi(z)]} + cc$$

where ω(z) is the spot radius at z

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

R(z) is the curvature of the wave fronts, which is:

$$R(z) = z\left[1 + \left(\frac{z}{z_R}\right)^2\right]$$

φ(z) is phase shift where:

$$\varphi(z) = arctg(\frac{z}{z_R})$$

We can also add the temporal phase term to the E field equation, then the final equation for a CW laser pulse will be:

$$E(x,y,z,t) = \sqrt{I_0}\, e^{[-\frac{x^2+y^2}{\omega^2(z)}]} e^{[-i\frac{k(x^2+y^2)}{2R(z)}]} e^{[i(\omega_0 t - kz + \varphi(z) + \varphi(t))]} + cc$$

Short laser pulses have a broad spectrum, which will determine the duration of the transform limited pulse. For describing a short laser pulse, we also need to add a temporal term, which normally is also a Gaussian function. Then, we can describe it as follows:

$$E(x,y,z,t) = \sqrt{I_0}\, e^{-\left(\frac{t}{t_p}\right)^2} e^{\left[-\frac{x^2+y^2}{\omega^2(z)}\right]} e^{\left[-i\frac{k(x^2+y^2)}{2R(z)}\right]} e^{[i(\omega_0 t - kz + \varphi(z) - \varphi(t))]} + cc$$

Whereω_0 is the carrier frequency of the pulse.

Description of Pulse in Temporal Domain:

As we can see in above equation, the description of short laser pulses is very complicated. Then, for simplicity we just look at the temporal profile of the pulse. We also ignore the complex conjugate term for simplicity. After all of these simplifications, the complex field will be:

$$E(t) = \sqrt{I(t)}\, e^{i(\omega_0 t - \varphi(t))}$$

Which ω_0 is carrier frequency of the pulse.

Description of Pulse in Frequency Domain:

In many cases, it easier to describe a pulse in the frequency domain. By using Fourier transformation, we can move from temporal to frequency domain. Then we have:

$$E(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E(t) e^{-i\omega t}\, dt$$

Then, we can write the electric field as follows:

$$E(\omega) = \sqrt{S(\omega)} e^{i\phi(\omega)}$$

Where $\phi(\omega)$ is called spectral phase, and $S(\omega)$ is called spectrum, which will be measured by the spectrometer. By using the frequency domain definition of a pulse, we can more easily describe the propagation of a pulse inside a medium.

4. Ultra-short Pulse Measurement and Correlation Technique

In the field of ultrafast optics, it is critical to have enough information about the temporal and the spectral profile of a pulse. There is a solid connection between the spectrum and the duration of a pulse. As we have mentioned before, for a Gaussian transform-limited pulse, we

have the following relation between the frequency bandwidth and the minimum pulse duration:

$$\Delta\nu\Delta t = \frac{2ln2}{\pi}$$

However, this equation is only valid for transform-limited pulses. If our pulse has higher order dispersion terms (like second order dispersion), the pulse will be broader. Then, the equation cannot describe the temporal behavior of our pulse. So, in this case, the spectrometer is not enough to reveal information about the temporal behavior of a pulse. We need to measure the pulse duration with other techniques.

Moreover, the laser pulses in the femtosecond regime are much faster than the temporal response of the electronics device. Then it is not possible to use oscilloscopes and photodiodes to measure the duration of ultrashort laser pulses. In order to measure the pulses in the femtosecond and attosecond regime, we can use a copy of a pulse as a gating function to get more information. This will be the basic concept of the autocorrelation technique.

In this method, we use a beam splitter to divide a pulse into two separate copies. By giving a delay to one of the pulses, they can spatially overlap inside a nonlinear medium. This can eventually cause to have nonlinear interaction such as the second harmonic generation (if the phase matching condition is satisfied). The intensity of the SHG pulse will be a function of the time delay between the pulses. The SHG's intensity will be as follows:

$$I_{SHG}(\tau) \propto I(t)I(t-\tau)$$

However, the electronic devices are too slow to measure the temporal behavior of the SHG' intensity. But, they can measure the intensity autocorrelation, which can be defined as follows:

$$A^2(\tau) = \int_{-\infty}^{+\infty} I(t)I(t-\tau)dt$$

It is clear that SHG generation can only happen if the two pulses are overlapping in time. Then, the intensity autocorrelation is a function of the temporal profile of the pulse.

So, the question is that what kinds of information we can get from the intensity autocorrelation of two optical pulses? It is clear that if the delay between the pulses be zero, the autocorrelation function has its maximum. Also, if the two pulses do not have any

overlap, the autocorrelation function will be zero. Autocorrelation has its ambiguities. The main three ambiguities are the direction of time, spectral phase information, and finally the unity of the results. Now, let us explain these ambiguities.

5. Conclusion

The primary goal of this research was to study the effect of the red-shifting process in MRG. We have seen that by pumping the SF6 in the transient regime, the Raman orders will have the redshifted shoulder, which even doubles the frequency bandwidth of each Raman order. This redshifting process can be useful to increase ultimate peak power of each pulse. Our results show that there is a temporal delay between the two pulses. We have used our prism pair to study this delay, and we have seen by changing the separation between the prisms the delay between the pulses will be changed. This change in the delay confirms that these two pulses are independent of each other. We have also seen that the by changing the prism separation the temporal duration of the pulses will change differently, or in the other word if we want to compress the Raman pulse, the red-shifting pulse will be broadened. This shows that they do not have the same spectral phase, which is very interesting for us.

References

1) K. Midorikawa, " High-Order Harmonic Generation and Attosecond Science" Japanese Journal of Applied Physics 50, Vol. 50, Number 9R, 2011.
2) U. Keller, "Ultrafast solid-state laser oscillators: a success story for the last 20 years with no end in sight," Appl Phys B, Vol. 100, Issue 1, pp 15–28, 2010.
3) S. Baker, I. Walmsley, J. Tisch and J. Marangos, "Femtosecond to attosecond light pulses from a molecular modulator," Nature Photonics 5, pages 664– 671, 2011.
4) H. Chan, Z. Hsieh, W. Liang, A. Kung and C. Lee, "Synthesis and measurement of ultrafast waveforms from five discrete optical," Science, Vol. 331, Issue 6021, pp. 1165-1168 ,2011.
5) D. Strickland, Z. Cui, M. Chaturvedi and H. Yan, "Multi-frequency Raman Generation with Chirped Pumping," JSAP-OSA Joint Symposia 2013 Abstracts, paper 18p_D5_1, 2013.
6) Z. Cui, M. Chaturvedi, B. Tian, J. Ackert, F. Turner and D. Strickland, "Spectral red-shifting of multi-frequency Raman orders," Optics Communications, Vol 288, pp. 118-121, 2013.

7) H. Yan, "Characterizing Transient Regime Multi-frequency Raman Generation by the Aid of Spectral Phase Interferometry for Direct Electricfield Reconstruction," Waterloo, 2013

8) P. Russell, "Photonic Crystal Fibers," science, Vol. 299, Issue 5605, pp. 358- 362, 2003.

9) F. Benabid , J. Knight, G. Antonopoulos and P. Russell, "Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber.," Science, Vol. 298, Issue 5592, pp. 399-402, 2002.

A. Weiner, Ultrafast Optics, John Wiley & Sons, Inc, October 2008.

10) E. Sali, K. Mendham, J. Tisch, T. Halfmann and J. Marangos, "High-order stimulated Raman scattering in a highly transient regime driven by a pair of ultrashort pulses," Optics Letters, Vol. 29, Issue 5, pp. 495-497, 2004.

11) A. Nazarkin, G. Korn and T. Elsaesser, "All-linear control of attosecond pulse generation", Vol. 203, Issues 3–6, pp. 403-412, 2002.

12) V.Kalosha, M.Spanner, J.Herrmann, and M. Ivanov, "Generation of single dispersion pre compensated 1-fs pulses by shaped-pulse optimized high-order stimulated Raman scattering", Phys Rev Lett, Vol. 88, Number 10, 2002.

13) E. Sali, K. Mendham, J. Tisch, T. Halfmann and J. Marangos, "High-order stimulated Raman scattering in a highly transient regime driven by a pair of ultrashort pulses," Optics Letters, Vol. 29, Issue 5, pp. 495-497, 2004.