Advanced Optical Developments for inter-Satellite Communication

Debabrata Goswami

Department of Chemistry, Indian Institute of Technology Kanpur

Abstract

One of the most common and effective usage of free space communication (FSO) is in the information transfer between satellites, which at present is mostly based on wireless Radio frequency (RF). FSO is a telecommunications technology that transmits and receives data in the form of optical signal through an unguided channel from one point to another point. The theory of FSO is essentially the same as that for fiber optic transmission. The difference is that the energy beam is collimated and sent through clear air or space from the source to destination, rather than guided through an optical fiber. While optical fiber has emerged as the major communication channel for terrestrial communication due to the difficulty of finding effective line of sight in terrestrial space needed for FSO, it remains as one of the most effective means for space applications, especially for inter-satellite communication. Our research is focusing on such advanced optical technology as the effective transmitter for free-space communication.

Introduction

In recent years, FSO technology has emerged as an attractive alternative to the conventional radio-frequency (RF) system, which is evident from a summary of the comparison between FSO and RF wireless communication as follows:

- Lower cost: The cost of disposing FSO is lower than that of an RF with comparable data rate. There are no cables to deploy, no expensive rooftop installations required. Based on a recent finding done by an FSO company based in Canada 'fSONA', the cost per Mbps per month based on FSO is about half that of RF based systems [1].
- Huge modulation bandwidth: Generally Optical carrier wavelength which includes infrared, visible and ultra violet comes within a range of few nanometers to few micrometers; correspond to a frequency of thousands of Terahertz which is far greater than RF frequency. In any communication system, the allowable bit rate of the channel determines its maximum bandwidth. Using optical frequency whose optical frequency ranges from 1012 - 1016 Hz could accommodate up to 2000 THz bandwidth. Thus information carrying capacity of FOS channel is highly increased with respect to RF capacity.
- Free from interference: Due to multi pass propagation of RF signal, fading is a very high problematic issue in radio wireless communication, but FSO seldom faces fading issue. Due to close proximity of RF carriers in RF spectrum, wireless RF communication faces inter-channel and intra-channel interference. Optical frequencies are out of these problems, which is a great advantage.
- Quick to deploy and redeploy: The time taken for an FSO link to become fully operational starting from installation down to link alignment could be as low as four hours. The key requirement is the establishment of an unimpeded line of sight between the transmitter and the receiver.

Given the bottleneck arising due to bandwidth, cost as well as fidelity issues, it has been proposed and targeted all the way from the dawn of the 21st century for complete optical communication for all Satellite-based applications [2]. Over the years, the European, Japanese and US space missions have made some progress and there has been a flurry of activities in past few years [3]. This emergence is due, in large part, to the increasing maturity of lasers and compact optical systems.

However, one of the very versatile approaches for typical electrical or RF signal to optical signal conversion schemes of using the Acoustic-optic modulator (AOM) [4] has been yet to be used for Satellite communication. AOMs are very useful devices, which allow the frequency, intensity and direction of laser beam to be modulated. They are one of the most effective tools in the conversion of electrical or microwave signals into optical signals. AOM consists of a piezoelectric crystal, which generates acoustic waves on its surface when radio frequency signal is applied on it. These acoustic waves travelling through a crystal can be modeled as crests of increased refractive index alternating with troughs of decreased refractive index. In most of the commercial AOMs, the waves are reflected back on itself to ensure a standing grating is created.

AOM transmitters can be used either in the traditional standing wave grating mode or in the travelling grating mode. Direct AOM modulation with light is enough for simple amplitude modulation; however, a multiplexed high-band transmission scheme would involve a Fourier domain pulse shaping with the AOM acting as a programmable transmission grating. Our novelty [4] has been in the fact that we have used the AOMs to have a non-reflective plane for the travelling waves to ensure faithful (hi-fi) conversion of the applied RF to the optical signal conversion. Interestingly, though AOM has been used in standing wave mode for decades, it is only recently; its travelling grating mode has become more appreciable. There is a great advantage of using the travelling wave grating mode for the AOM while using it as an effective transmitter for both continuous as well as pulsed lasers. Satellite communication would benefit largely from the use of such devices both from bandwidth, cost as well as fidelity issues.

Our research of bringing in the use of the well-established AOM as optical transmitter has, therefore, put ISRO as a front-runner in the free-space optical communication for satellite application. However, of the major issues in space communication that would highly benefit ISRO is the fact that the high-bandwidth communication would occur with the least possible hardware scaling requirement wherein the future usage of electro-optic modulator (EOM) with its immense modulating bandwidth sustainability would further this communication scheme with least hardware scaling. Our model research with AOM would pave the way for the novel idea of putting this forth this approach. It is also worth mentioning that this same technology can be immensely useful in areas where laying optical fibers can be immensely difficult or impossible [5].

Setting up of the pulse shaper

We use a carrier driver frequency for the AOM, which is modulated as per the transmission electrical signal for building our transmitter part. Once the optical transmitter is generated it can be transmitted over free space and a simple optical detector can be used for reading back the signal. We need a complex RF adder for the electrical signals to be embedded with the driving RF signal into the AOM. Once that is in place, it can be used to encode dual channel signal information.

Altering any of the pulse parameters, such as, Amplitude, Frequency, Phase, Inter and Intra-pulse separation changes the shape of the output pulse. The optical pulse shaping approach is generally based on the well-known concept in electrical engineering: linear, time-invariant filtering scheme. Time invariant filter means that transfer function does not change with time. Linear filtering is commonly used to process electrical signals ranging from low frequency (audio and bellow) to very high frequencies (microwave). Linear filtering can be described in either the time domain or in the frequency domain. So if optical pulse is allowed to pass through the pulse shaping system, where pulse shaping system behaves like a linear, time-invariant filter. This system changes some characteristics of pulse and thus desired shaped pulse could be achieved. Of course, the hardware needed for programmable linear filtering of laser pulses looks very different from the familiar resistors, capacitors and inductors used for linear filtering of conventional electrical signals. In electrical engineering, a couple of resisters and inductors are sufficient to construct a filter but that is not so in optical pulse shaping.

Modulation in time domain is difficult as electronic devices are too slow (~10^{-9} s) to be able to respond in femtosecond time scale. So the modulation is done in frequency domain, where the output electric field is modulated in the Fourier domain: $E_{out}(w) = E_{in}(w)H(w)$. This is shown schematically in Figure 1. First to get desired waveform we have to construct the static grating in the acousto-optic modulator (AOM) plane. To do that we need basic electrical circuitry schematically represented in Figure 2. First two different output waveforms generated in wave generator LeCroy LW420A are mixed with split carrier waveform to produce two different modulated signals which are then combined by 180o RF

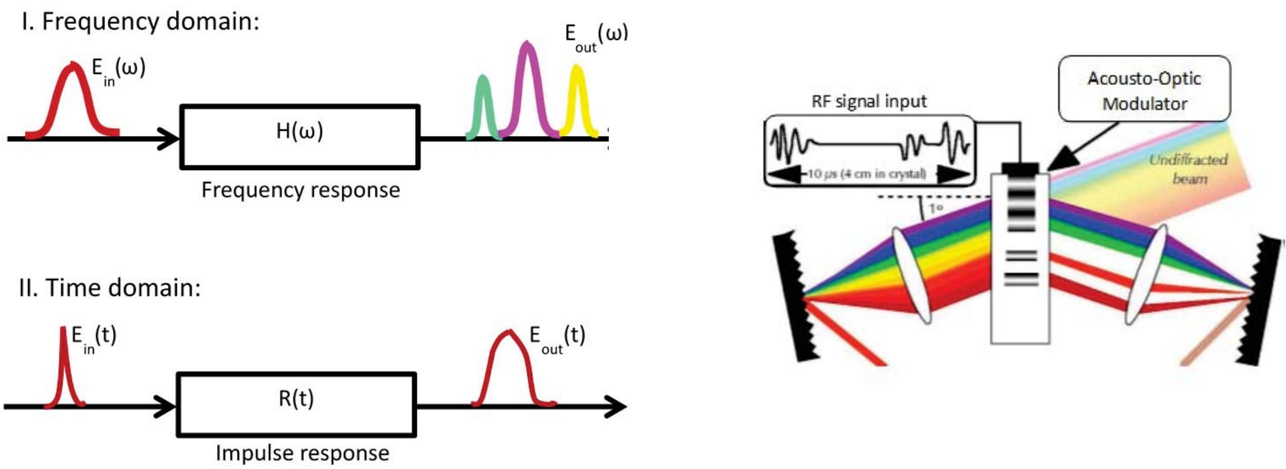

Figure 1. Pulse Shaping schematic: Principle of (a) time domain shaping and (b) frequency domain shaping, which is the more practical one for ultrafast lasers and is translated into (c) Experimental Fourier Optical domain shaping with AOM.

combiner. The combined output is passed through DC and then followed by RF amplifier to give final input to AOM. To control the waveform generator via computer we have performed a program in LabVIEW. We use a carrier driver frequency for the AOM, which is modulated as per the transmission electrical signal for building our transmitter part. Once the optical transmitter is generated it can be transmitted over free space and a simple optical detector can be used for reading back the signal. We need a complex RF adder for the electrical signals to be embedded with the driving RF signal into the AOM. Once that is in place, it can be used to encode dual channel signal information.

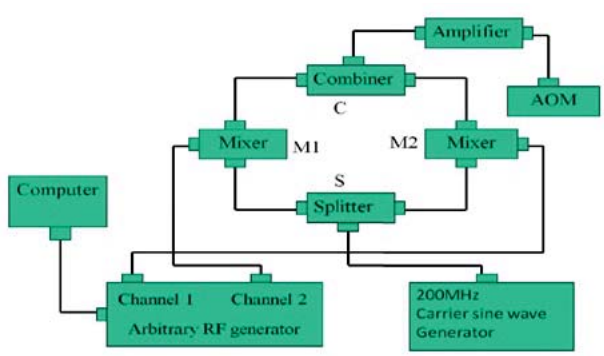

Figure 2. Schematic of the RF mixer to generate desired modulation in the carrier RF frequency.

Pulse Shaping Results

Since AOM is a travelling wave modulator, the diffraction grating must be updated repetitively with the same RF pulse. Since the acoustic wave takes some finite time to travel through the crystal, it's important that the laser pulse interacts with the AOM only when the complete aperture of the crystal is written with the acoustic modulation depending on the RF wave. Any asynchrony of arrival time between the laser pulse and modulation function from the RF wave onto the crystal will modulate the signal in an inefficient way. Ideally at generation of each pulse from the laser output the arbitrary wave generator (AWG) should be triggered to send the RF wave.

We started by applying a square pulse in one channel and keeping the other channel at zero. The band-width of the square pulse is varied from 1 MHz to 7.5 MHz. At lower bandwidth i.e. when the time duration of the square pulse is high it creates the acoustic wave pattern within the AOM crystal in such a way that all the frequency components of spatially dispersed pulse are diffracted equally. So the Gaussian shape of the input pulse in reproduced in the output pulse. Increase of bandwidth of the RF pulse means decreasing its time duration. So the acoustic wave pattern created in the crystal is changed. As a result the output shape of the pulse also keeps changing and it assumes sinc function type appearance (Figure 3). The situation is equivalent to the fact that the square window selectively diffracts some of the frequency components which after re-collimation by the 2nd grating gives the newly shaped pulse. The next step was to introduce some phase variation in the output pulse shape. We started with sine wave in one channel while keeping the other channel blank. After applying this we observed that the peak starts to divide around 1.75 MHz bandwidth and completely separated pair of peaks appear around 5 MHz. This is probably because of the frequency sweep that sine wave introduces (Figure 4). To demonstrate the effect of phase and amplitude modulation we explored what happens if

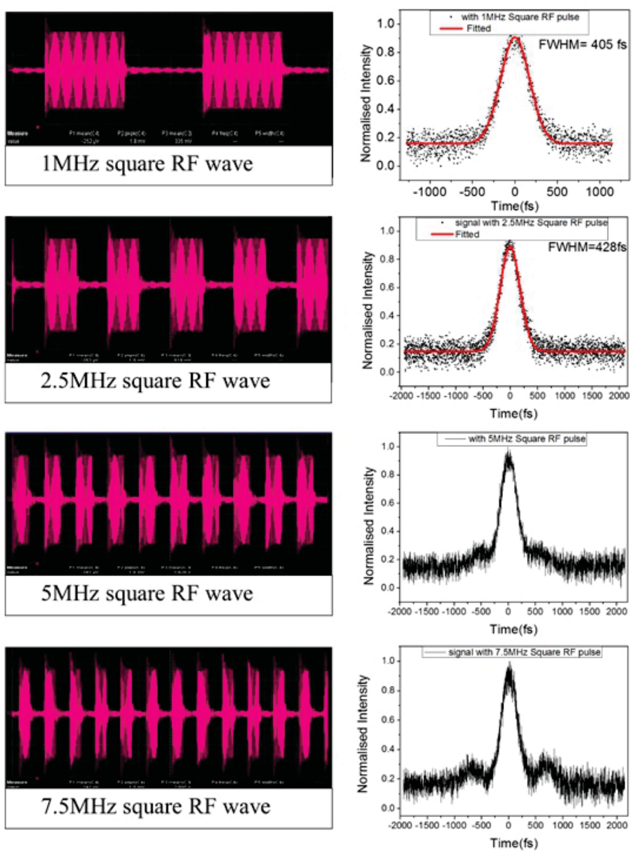

Figure 3. Application of RF square pulses at certain frequencies from only one channel modulation to the AOM (left side) and the corresponding output pulse (right side) as measured through cross-correlation with the original unmodulated pulse.

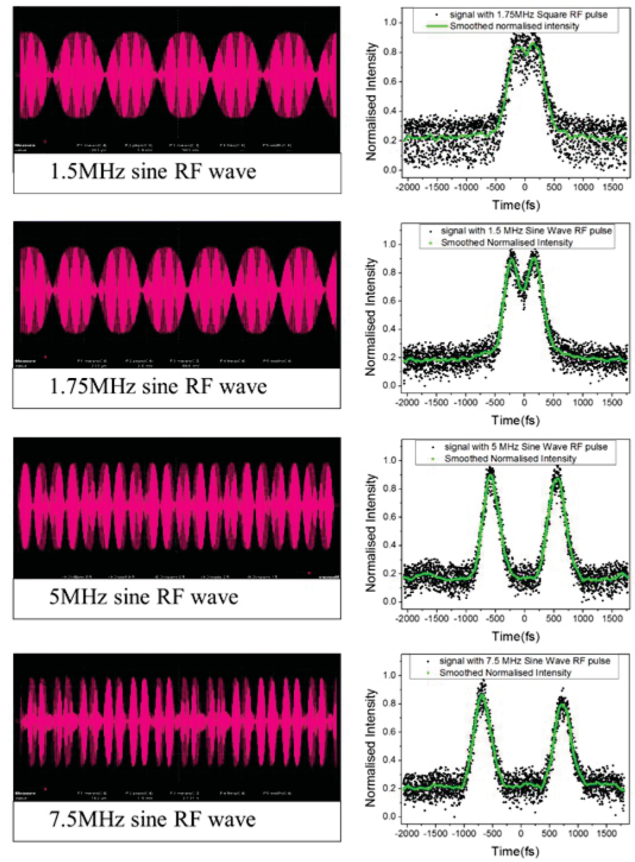

Figure 4. Application of RF sine pulses at certain frequencies from both channel modulation to the AOM (left side) and the corresponding output pulse (right side) as measured through cross-correlation with the original unmodulated pulse. Note the pulse splitting effect.

RF pulse is sent in both of the arms we applied sine wave in both arms and following figures show our results. The qualitative pattern of the shape does not differ too much from the shape obtained by applying sine wave at single channel. Thus, the shape of the output pulse is completely dependent on the shape and duration of the RF pulse which is in our control.

New Wideband source development

As a part of this research on optical communications, we have also initiated and explored novel wideband optical source exploration. We have generated femtosecond induced super-continuum as it is a popular coherent source for broadband optical communication. We have looked into the various properties of supercontinuum generation [6] as a function of several experimental parameters. For this purpose we have used a femtosecond laser system that can generate Ti:Sapphire pulses having pulse-width of ~50 fs at variable pulse repetition rate ranging from a kHz to a few Hertz. These pulses were focused onto the samples to generate the femtosecond continuum for the incident laser pulses. We utilized the unique variable repetition rate of this femtosecond laser to study the effect of individual versus cumulative pulses in the white-light generation process.

We generated super-continuum in liquid water as well as in air as a test case to explore the effect of laser repetition effect, which has not been investigated before. We have found as shown in Fig. 5, there is a large dependence of the super-continuum generation process on the laser repetition rate of the laser.

We can explain this as follows. The generation of the first step of super-continuum process is due to the self-focusing, which happens only if the Input laser power reaches a threshold value PTh. This self-focusing is in

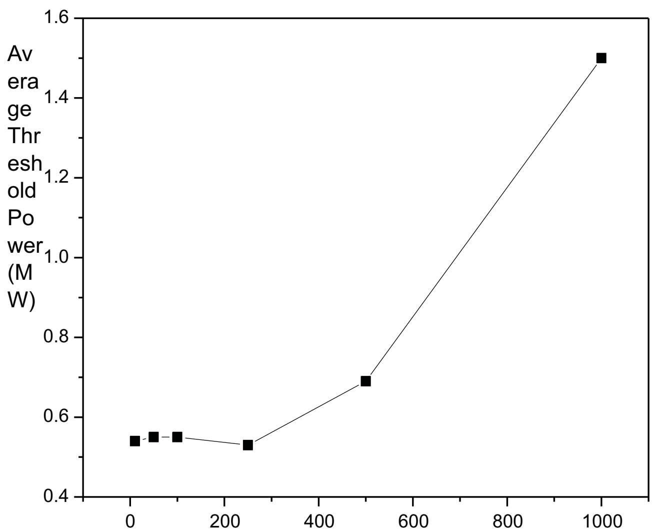

Figure 5. Threshold power needed to generate super-continuum at different repetition rate changes with different laser repetition rate

continuous competition with the self-defocusing effect of electrons generated via multi-photon excitation. Thus the threshold laser peak power needed for the super-continuum generation decreases with the increasing repetition rate of the laser though the average power of the laser increases with increasing repetition rate. Consequently, we get the dependence as shown in Figure 5. This interesting result is under further investigation.

Conclusion

The principle of impacting a travelling grating onto the optical field is the most important concept we have shown working in principle wherein we have attempted both digital and analog transmission. We use ultrafast pulsed lasers using the Fourier interaction mode, where the full bandwidth of the AOM can be imposed on the mode locked pulse train (spectral bandwidth of the laser pulse is available in the Fourier plane) while still leaving the transmission channel to be dark for >99.99% of the time, thus permitting time-domain multiplexing (TDM) to Tb/s communication rate.

Studies on the wide band super-continuum generation as shown by us also shows our capability in controlling the efficiency of the process as well as in understanding the underlying concept in the generation of such a highly nonlinear process.

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Professor Debabrata Goswami is an expert of ultra-fast laser technology. He has pioneered the use of control ideas with femto-second pulse shaping in spatio-temporal control, quantum computing, microscopy, etc. After receiving Master's degree from IIT Kanpur, Dr. Goswami went to US with multiple scholarships to receive his PhD from Princeton University and completed his postdoctoral Fellowship at Harvard University in 1995. After several research jobs in US, he returned to India in 1998 as a Faculty in TIFR (Mumbai). He moved to IIT Kanpur in 2004, where he continues as the Professor of Chemistry. He is the recipient of several academic and research accolades, including the Wellcome Trust International Senior Research Fellowship (UK), Swarnajayanti Fellowship and Thathachary Science Award (India). He is a member of several academic and professional societies and councils. He has published over hundred research articles, several book chapters, edited conference proceedings and books. He has popularized Science Education and is a popular K12 teacher on Indian television. He is also an honorary faculty of the Fab-academy, which champions worldwide spread of hands-on education. The work reported here is an effort with the ISRO-STC research.