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13. ABSTRACT *(Maximum 200 words)*

This research project is currently supported in part by the NSF, ARPA-OTC II and AFOSR. We are extending the research on artificial dielectrics to nonlinear optical composites which have been recently proposed to BMDO and AFOSR.
The instrumentation and equipment requested will enable basic research on nonlinear optics of ultrashort pulses for ultrahigh bandwidth (e.g., over 1 Tbits/sec) communication applications. In particular, this novel approach will investigate devices and optical network systems for enhanced information transmission rate, network controllability and reliability, network security using quantum and classical cryptography. The requested equipment will be used to investigate the effects of the fiber optic and/or free space communication channel on the signal fidelity, linear and nonlinear dispersion, and the effects of fiber optic amplifiers. This equipment will also enhance experimental work on implementation of multidimensional optical channel using ultrashort pulse nonlinear spectral holography, and design and fabrication of nonlinear artificial dielectric materials that utilize near field effects to increase their efficiency.
In addition, the equipment requested will significantly enhance the overall characterization and processing capability within the Department of Electrical and Computer Engineering at UCSD. Graduate and undergraduate students will benefit from access to this fabrication and characterization equipment.

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Final Report

1. Request for Instrumentation

1.1 Abstract

The requested equipment and instrumentation (being submitted to both the BMDO and the AFOSR programs) will enable continuation of the research program on "Photonic Imaging Networks" at the University of California, San Diego, supported by the DOD's Focused Research Initiative (FRI) Program of BMDO via AFOSR . Additionally, the requested equipment will be used in our currently funded AASERT project on "Quantum and Classical Cryptography for Security and Privacy of Photonic Networks," and the currently proposed project on "Nonlinear Spatio-Temporal Processing of Femtosecond Pulses for Ultrahigh Bandwidth Communication." In addition, the requested equipment and instrumentation will provide the necessary tools to enhance the ongoing research program on composite and artificial optical materials research on diffractive optics with multifunctionality and programmability. This research project is currently supported in part by the NSF, ARPA-OTC II and AFOSR. We are extending the research on artificial dielectrics to nonlinear optical composites which have been recently proposed to BMDO and AFOSR.

The instrumentation and equipment requested will enable basic research on nonlinear optics of ultrashort pulses for ultrahigh bandwidth (e.g., over 1 Tbits/sec) communication applications. In particular, this novel approach will investigate devices and optical network systems for enhanced information transmission rate, network controllability and reliability, network security using quantum and classical cryptography. The requested equipment will be used to investigate the effects of the fiber optic and/or free space communication channel on the signal fidelity, linear and nonlinear dispersion, and the effects of fiber optic amplifiers. This equipment will also enhance experimental work on implementation of multidimensional optical channel using ultrashort pulse nonlinear spectral holography, and design and fabrication of nonlinear artificial dielectric materials that utilize near field effects to increase their efficiency.

In addition, the equipment requested will significantly enhance the overall characterization and processing capability within the Department of Electrical and Computer Engineering at UCSD. Graduate and undergraduate students will benefit from access to this fabrication and characterization equipment.

The requested instrumentation and equipment consists of

- Ultrafast Spectrum Analyser, Diagnostic B, Spectra Physics, Single Shot Autocorrelator, Model SSA-F, Spectra Physics, and Oscilloscope, Tektronix Model TDS-640A are requested for diagnostics and analysis of the spectral bandwidth of the tunable femtosecond laser system that will be used in our SPD, PSM, and optical communication link.
- Scanning Autocorrelator, LZF-0198, Inrad Inc. is requested to characterize the shape of the pulses generate in PSM.
- Mach-Zender Optical Modulator,10-150-1-3-C1-AP, UTP, Amplifier, 20T4G18, Amplifier Research, and the Signal Generator, HP 83732B, HP are requested to implement the PSM for optical communication link.
- Photodetector, 1014, New Focus Inc. and Digital Oscilloscope, HP 54750A and HP 54752A are requested to implement the SPD of the optical communication link.
- RF Magnetron Sputtering System that will be built of components listed below (see budget item # 11 (a) through (d)) is requested for fabrication of composite nonlinear optical materials.
- Data acquisition and laboratory controller (Pentium with interfaces and accessories) IBM, is r equested to interface and control the electronic and electrooptic components of the experiments.

2. Supporting Information

2.1 Contribution to research currently proposed to DOD

The requested equipment and instrumentation (being submitted to both the BMDO and the AFOSR programs) will enable continuation of the research program on "Photonic Imaging Networks" at the University of California, San Diego, supported by the DOD's Focused Research Initiative (FRI) Program of BMDO via AFOSR. Additionally, the requested equipment will be used in our currently funded project on "Quantum and Classical Cryptography for Security and Privacy of Photonic Networks," (Y. Fainman, PI, AFOSR) and the currently proposed project on "Nonlinear Spatio-Temporal Processing of Femtosecond Pulses for Ultrahigh Bandwidth Communication." The UCSD's research project on "Photonic Imaging Networks" (Y. Fainman, PI and A Kellner, co-PI) is a part of the Graphics Server Consortium (L. Milstein, Director) within the FRI Program, supported at a level of about $500,000/year. Its main objectives include research of ultrahigh bandwidth coherent optical communications and network architectures, quantum and classical cryptography for network security, and medical image communication over optical networks. In addition, the requested equipment and instrumentation will provide the necessary tools to enhance the ongoing research program on composite and artificial optical materials research on diffractive optics with multifunctionality and programmability. This research project is currently supported in part by the NSF, ARPA-OTC II and AFOSR. We are extending the research on artificial dielectrics to nonlinear optical composites which have been recently proposed to BMDO and AFOSR.

The instrumentation and equipment requested will enable basic research in the field of the nonlinear optics of ultrashort pulses in conjunction with ultrahigh bandwidth (e.g., over 1 Tbits/sec) communication applications for transmission of images and image format data. In particular, this novel approach will be investigated in conjunction with basic research on devices and optical network systems for enhanced information transmission rate, network controllability and reliability as well as network security and privacy utilizing methods of quantum and classical cryptography. The requested equipment will be used to investigate the effects of the fiber optic and/or free space communication channel on the signal fidelity, including the effects of linear and nonlinear dispersion and its compensation, the effects of fiber optic amplifiers, etc. The requested equipment will also enhance experimental works such as implementation of multidimensional optical channel using ultrashort pulse nonlinear spectral holography, demonstration of enhanced bandwidth quantum cryptographic communication channel for secret key generation over a photonic network, and design and fabrication of nonlinear artificial dielectric materials that utilize near field effects to increase their efficiency.

In addition, the equipment requested will significantly enhance the overall characterization and processing capability within the Department of Electrical and Computer Engineering at UCSD; this improvement will benefit a wide range of DoD-funded research programs at UCSD. Graduate student researchers will benefit by being directly involved with the fabrication and characterization process of their devices and systems. The proposed work, executed in the Department of Electrical and Computer Engineering at the University of California, San Diego will also have a strong impact on the education of students at the graduate and undergraduate levels.

2.1.1 Introduction and Motivation

Ultrashort pulse laser technology has recently experienced significant advances, producing high peak power pulses of optical radiation few femtoseconds in duration, corresponding to only a few cycles of its fundamental frequency.[1-4] Future progress in this area is inevitable due to the unique properties of ultrashort laser pulses that are crucial for various science and engineering applications including optical communications,[5,6] medical and biomedical imaging,[7-11] chemistry and physics.[12-14] A common feature of these applications relies on our ability to control the shape of the ultrashort pulses as well as, conversely, our ability to detect the shape of the ultrashort pulses.

In communication applications, pulse laser technology enables the bandwidth and the efficiency of fiber optic communication systems to exceed those of electrical cable systems. Presently, we are far from realizing the potential performance of optical networks. Electronic devices and systems connected to optical networks may reach bit-rates on the order of 1-10 Gb/s. In contrast, the maximum bit-rate of a photonic network may exceed 1 Tb/s. The 2-3 order-of-magnitude mismatch between fiber and electronic device capacities can be used to increase the speed, reduce the latency, or increase the security and reliability of the data transmission. To implement these applications, it will be necessary to construct an all-optical pre-processor at the transmitter and a post-processor at the receiver which will perform multiplexing and demultiplexing, respectively (see Fig. 1). The multiplexer performing space-to-time transformation will combine relatively slow but parallel electronic channels into an ultrahigh bandwidth serial fiber optic channel (i.e., parallel-to-serial conversion), whereas the demultiplexer will perform the inverse time-to-space transformation for electronic detection (i.e., serial-to-parallel conversion). For efficient bandwidth utilization, these processors need to operate at rates determined by the bandwidth of the optical pulses.

Our system approach is described schematically in Fig.1. We consider using the Terabit Optical Rate Sequence (TORS) generating system, where the input data (e.g., serial data from a serial computer or parallel data from a parallel computer, image processor or page-oriented memory) is first converted into a sequence of short pulses (each of about 100 fsec). A number of different schemes for implementing the TORS system (e.g., pulse shapers, array of modulators with relative time delay, etc.) exist. The data stream from the TORS system is then either transmitted through the network to the recipient or is introduced into the Spectral Domain Optical

Storage (SDOS) system, where, for example, the terabit rate time sequence of data is transformed into the spectral domain and stored.[15,16] When the stored data is read out of the SDOS system, the output spectrum is converted back into time sequence and sent through the all-optical fiber network. At the user node the time sequence is converted to lower rate parallel channels in space domain for electronic detection using a femtosecond rate demultiplexer, Ultrashort Pulse Image Converter (UPIC).

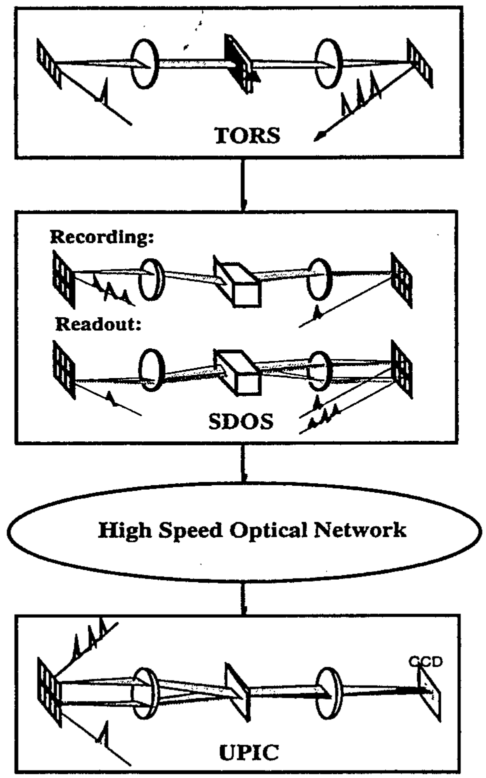

Fig. 1 Block diagram of Spectral Domain Optical Storage system interfaces.

This research is a continuation of the Focused Research Initiative program on Photonic Imaging Networks of BMDO/AFOSR. The proposed research will focus on the study of the nonlinear spatio-temporal processing technology to achieve real-time optical space-time signal conversion for ultrahigh bandwidth communication and on the investigation of the effects of the communication channel on the signal fidelity. The unique feature of our approach include developing techniques that are capable of self-compensation for the signal distortions due to propagation through the communication channel (e.g., fiber dispersion, turbulence in free space, etc.), which is critically important not only for the next generation fiber optic TDM networks, but also for free space satellite communications. Furthermore, in contrast to telecommunications applications where WDM techniques may be sufficient, our approach using TDM techniques is most suitable in satisfying the synchronization demands of computer networks. In the proposed research we will emphasize the development of high speed and high efficiency parallel-to-serial multiplexers (PSM) and serial-to-parallel demultiplexers (SPD)–the two most critical challenges for the current technology. To achieve our goal, we will explore different nonlinear optical processes, such as cascaded second-order nonlinearities, quasi-phase-matched nonlinear wave mixing, as well as studies of enhancing nonlinear wave mixing employing composite optical nonlinearties.

In the proposed research we emphasize developing high speed and high efficiency parallel-to-serial multiplexers (PSM) and serial-to-parallel demultiplexers (SPD), the two most critical challenges for the current technology to meet the needs of ultra-high bandwidth communication applications. In the following we describe the proposed research on PSM system using cascaded second order nonlinearity, as well as on design, fabrication and testing of novel nonlinear artificial optical materials (e.g., quasi-phase-matching nonlinearties and composite nonlinear microstructures) for nonlinear three-wave mixing to achieve a fast and efficient SPD system. In addition, we will investigate devices and system related issues involved in the transmission of such signals through a practical fiber optic and/or free-space communication channel.

2.1.2 Multiplexers and demultiplexers for ultrahigh bandwidth communications.

The most promising technique to implement the TORS generating or PSM system uses spectral domain pulse shaping. This device is based on spectral decomposition of an ultrashort transform limited laser pulse into the spectral domain, modifying the pulse spectrum by using a 1D fixed[17] or programmable[18,19] spatial mask and recombining the modified temporal spectrum back into the time domain to form a shaped pulse. This technique has been shown to produce femtosecond shaped pulse trains with terahertz repetition rate, high resolution, and high fidelity.[20] Despite the unique capability of producing high quality shaped pulses, the existing spectral domain pulse shaping devices do not meet the speed requirements for ultra-high bandwidth optical communication applications. The pulse shaping devices rely on the speed of converting the spatial frequency content of the parallel spatial channels into the temporal frequency spectrum of an ultrashort pulse. The first devices used fixed spectral filters that require prior calculation and fabrication of Fourier transform computer generated holograms (CGH) corresponding to the parallel input channels.[21] Performing such calculations and short pulse spectrum modulation in real time will require not only very fast computation, but also very fast I/O bandwidth spatial light modulators (SLM) that can meet the spatial resolution and the dynamic range of such spatial Fourier transform CGH. The liquid crystal SLMs[18] and the acousto-optic SLMs[19] that are currently being used for the dynamic pulse shaping, have limited speed, resolution, and dynamic range, limiting their potential use for ultra-high bandwidth optical communication applications.

We have addressed some of these difficulties by introducing an all-optical parallel-to-serial processor that is capable of converting directly spatial optical signals into temporal shaped pulses with one-to-one correspondence[22]. Our approach is based on combining optical information processing that uses spectral holography[23-26] with that of conventional spatial Fourier transform holography. Our processor consists of two independent optical channels for carrying the temporal and the spatial information. The temporal information-carrying channel consists of a pair of gratings and a 4-F lens arrangement. The incident pulses are transformed by the input grating and the first lens into a temporal frequency spectrum distribution in space at the focal plane, while the second lens and the output grating perform the inverse transformation of the temporal spectrum distribution back to the time domain. The spatial information-carrying channel is a simple optical spatial Fourier transform arrangement consisting of the input image plane and a beamsplitter to share the second lens of the temporal channel. To achieve interaction between the temporal and spatial frequency spectral information we use a real time holographic material in a degenerate four-wave mixing arrangement. In our preliminary experiments, the speed of this parallel-to-serial conversion is limited by the time response of the bulk photorefractive material, which, depending on the material, can vary in the seconds to microseconds range. Recent studies of photorefractive multiple quantum well (MQW) devices[27] decreased the time response to the sub-microsecond range, which is still far from meeting the speed requirements of ultra-high bandwidth optical communication applications. Furthermore, MQW devices will limit the conversion efficiency (about 0.1%) due to inherently small thickness, limiting the interaction length in the device. In summary, to meet the practical needs of the PSM system approach, it will be essential to increase the signal conversion speed and the conversion efficiency, which are the two main objectives of our proposal to BMDO/AFOSR.

To meet the speed requirements of the ultra-high bandwidth optical communication channel, the PSM system needs to be operated in real time, i.e., as fast as the time window of the time-multiplexed shaped pulse packet usually in the range of 10-500 psec. We propose to use nonlinear optical processes such as nondegenarate four-wave mixing to achieve real time operation. Such nonlinear 4-wave mixing techniques usually suffer from low conversion efficiency due to relatively small values of $\chi^{(3)}$ in nonlinear optical materials. However, recent studies in Cascaded Second-order Nonlinearity (CSN)[28-33] might provide a solution to this problem. The CSN is based on cascading two second-order nonlinear interactions in a second-harmonic generation experiment, resulting in accumulation of nonlinear phase matching of the fundamental field. The CSN approach has been used to achieve spatial soliton,[28] self-diffraction,[29] as well as all-optical switching via optical Kerr effect,[32,33] which are usually possible with third order optical nonlinearities. Since the normal phase-matching condition is no longer imposed by CSN, the conversion efficiency of this process can approach 100 % when long interaction length is used.[30] Recent experiments have demonstrated 15% conversion efficiency for CSN in a 1-mm-thick BBO crystal.[32]

The ultrafast pulse image converter or SPD performs serial-to-parallel demultiplexing of the shaped pulse train created by the PSM system back into parallel spatial domain for electronic detection. The speed requirement of SPD is even higher than PSM, since the conversion speed needs to match the bit rate of the temporal signal generated by the PSM (in the range of THz). The purpose of the SPD is to "slow down" the pulse signals by converting the signals into parallel channels where each channel possess a reduced bit rate of 10-100 GHz that is within the bandwidth of the electronic detectors. Therefore, the concern here is how to achieve an optical serial-to-parallel conversion with such high speed. Again exploiting high speed and high efficiency nonlinear optical four-wave[26] and three-wave mixing[34,35] will be our main objective in meeting the needs of the ultra-high bandwidth communication application. Since the photorefractive four-wave mixing approach suffers from slow time response and does not meet the speed requirements of the UPIC system, we have demonstrated an alternative approach based on nonlinear three-wave mixing that overcomes the speed limitations of photorefractives.

A. Fast serial-to-parallel converter

Our UPIC or SPD system[36] is capable of real-time conversion of a femtosecond pulse sequence into its spatial image. The approach employs nonlinear spectral domain 3-wave mixing in a crystal of LiB_3O_5 (LBO), where the spectral decomposition waves (SDW) of a shaped femtosecond pulse are mixed with those of a transform limited pulse to generate a quasimonochromatic second harmonic field. Through this nonlinear process, the temporal frequency content of the shaped pulse is directly encoded onto the spatial frequency content of the second harmonic field, producing a spatial image of the temporal shaped pulse similar to that of the time imaging[37].

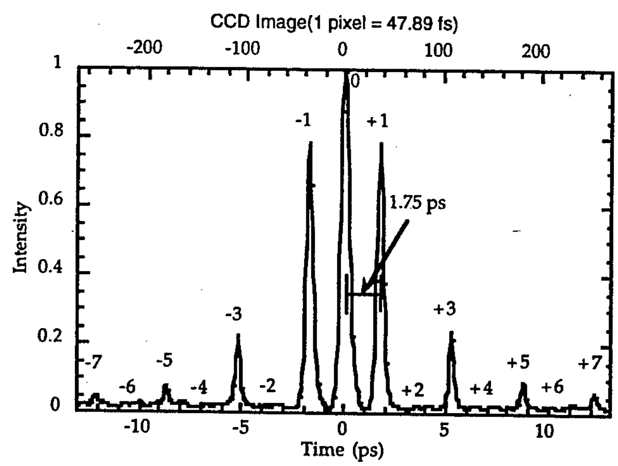

Fig. 2 The images of shaped pulses obtained with femtosecond pulse imaging system. The shaped pulses are obtain using a pulse shaping device with spectral filter implemented by a Ronchi grating.

The femtosecond laser output is split into two beams, one to be used as a reference beam and the other sent into a pulse shaping device to create a shaped pulse. The shaped pulse and the reference pulse beams are then introduced into the pulse imaging system of Fig. 1 (i.e., UPIC). In our experiments, we use as a spectral filter in the pulse shaping device, TORS, a 50/50 binary amplitude Ronchi grating. Such a grating has a unique property in that its Fraunhofer diffraction pattern does not have even diffraction orders except the zeroth order. The pulse image (see Fig. 2) clearly shows that the even order pulses in the sequence (except the 0 order) do not appear. The three central pulses (i.e., -1, 0, +1 orders) are close together while the other pulses (corresponding to higher orders) are separated by twice the distance. We estimate the distances between the center pulses to be 1.75 picoseconds which is consistent with the theoretical prediction. In addition to the ability to produce a high fidelity and real-time shaped pulse image, we also demonstrated that such time-to-space conversion via UPIC carries both amplitude and phase information on the shape of the femtosecond pulses.

In the SPD system, we used a Ti:Sapphire laser that produces 200 femtosecond pulses of 10 nJ per pulse at a rate of 77 MHz. The measured conversion efficiency of the 3-wave mixing is relatively low (0.1%) due to the spatial chirping of the pulse that reduces the peak power density necessary for nonlinear conversion. However, in our experiments, with the energy of the single pulse on the order of 1-10 nJ, the image intensity of the second harmonic field was found to be sufficient for CCD detection with video rate integration time. For PSM application, the integration time will reduce to nanosecond level and thus the second harmonic field will be more difficult to detect. Therefore, for practical applications we need to increase the conversion efficiency at least by one order of magnitude.

B. Fast parallel-to-serial converter

The photorefractive four-wave mixing approach used in our PSM system was employed to resolve the problems of spectral filtering in terms of resolution and dynamic range, but it did not meet the speed requirements of the ultra-high bandwidth communication system applications. To overcome the speed limitations of the photorefractive nonlinearities we propose to employ nondegenerate four-wave mixing using CSN, which possesses ultrafast time response, thus meeting the speed requirements of the PSM system. The function of the four-wave mixing process is to encode in real time the spatial frequency Fourier spectrum of the parallel optical input signal onto the temporal frequency spectrum of an ultrashort laser pulse. The proposed nondegenerate four-wave mixing PSM system is based on CSN that is accomplished by two cascaded type II three-wave mixing processes: a second harmonic generation followed by a type II down conversion process (see Fig. 3).

Consider that three incident fields are introduced into the CSN device: the short pulse spectral decomposition field, $E_{p,H}$, the cw input spatial frequency modulated field, $E_{s,V}$, and the cw reference field, $E_{r,H}$, where the subscripts H and V denote the polarization of each field. The field $E_{p,H}$ propagates along the optical axis of the system (k=0), whereas the fields $E_{s,V}$ and $E_{r,H}$ are collinear and both propagate at an angle with respect to the propagation direction of the field $E_{p,H}$, corresponding to a spatial frequency carrier, k. The overall process of the phase matching conditions in the CSN employed in a four-wave mixing arrangement consists of two steps summarized in Fig

3b. In the first step, the incident fields $E_{p,H}$ and $E_{s,V}$ interact, generating a second harmonic field (SHF) propagating in a bisector direction between the fields $E_{s,V}$ and $E_{p,H}$. This second harmonic field (shown by the dashed line in Fig. 3b) carries the spatial frequency information from the cw field $E_{s,V}$ and the temporal frequency spectrum of the ultrashort pulse field $E_{p,H}$. Note that the spatial carrier frequency (i.e., propagation direction) of the SHF needs to be adjusted for the new,

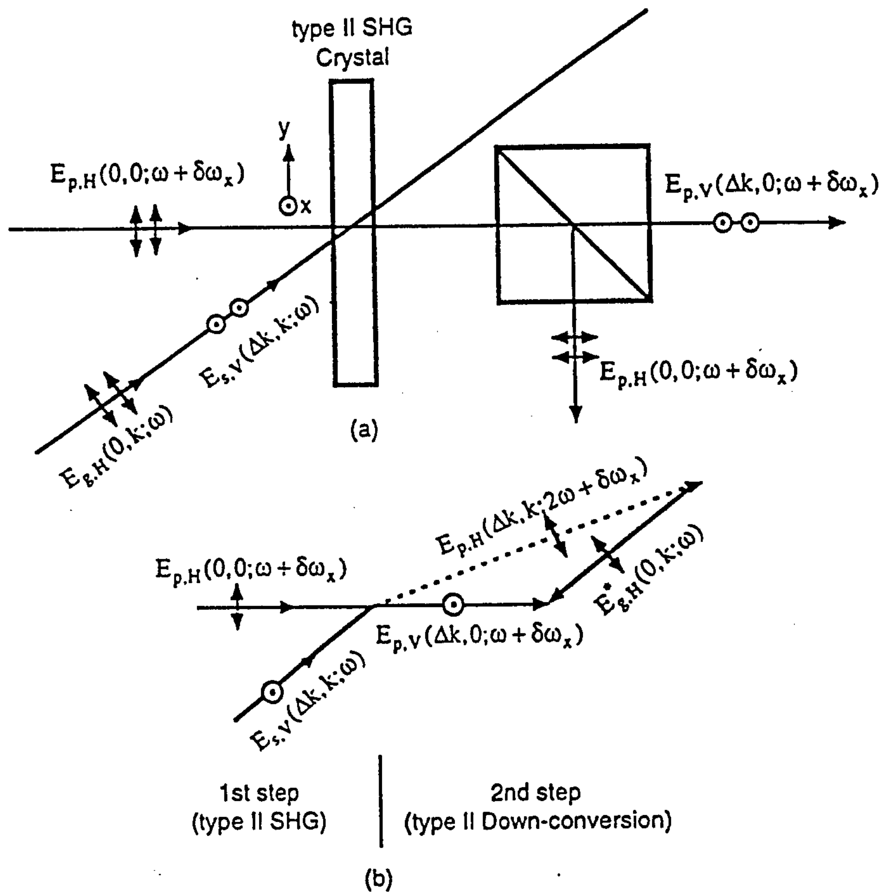

Fig. 3 Four-wave mixing utilizing a CSN: (a) schematic diagram of the device geometry, (b) description of the phase matching condition of four-wave mixing using CSN

doubled frequency, resulting in a wavevector twice as long as that of the fundamental frequency, but at smaller inclination angle. In the second stage of CSN, a down conversion process takes place by the interaction between SHF (produced from the first step) and the cw field $E_{r,H}$ generating at the output a fundamental frequency field $E_{p,V}$, which is vertically polarized and propagates collinearly with the incident field $E_{p,H}$. These two output fields can be separated by a polarization selective beam splitter as shown in Fig. 3a. The new, generated output field $E_{p,V}$ possesses a temporal frequency spectrum similar to that of a short pulse, but it also carries the spatial frequency information, Δk, that has been transferred from the SHF via the down conversion process. The result of such a CSN can be described by the following four-wave mixing relation,

$$E_{p,V} \propto E_{p,H} E_{s,V} E^{*}_{r,H} \qquad (1)$$

The CSN four wave mixing process is carried out in real-time with femtosecond time response, thereby meeting the speed requirements of the multiplexer for ultra-high bandwidth communication applications. The conversion efficiency of the CSN process is much higher than that of the four-wave mixing using conventional 3rd order optical nonlinearities. However, initially, we expect that the conversion efficiency will be lower due to the necessary spatial chirping of the optical pulses. Therefore, the second objective of our proposal will focus on improving the conversion efficiency of the nonlinear processes within our PSM and SPD systems. We propose to explore two alternative approaches: (i) study of spectral hole burning materials and (ii) improvement in the conversion efficiency of the nonlinear processes. For the first approach, we will closely coordinate and collaborate our efforts with the SRI group led by Dr. Kachru, one of the world leaders in spectral hole burning materials and their applications to time domain storage and information processing systems. We anticipate that the spectral hole burning materials will enable real-time spectral-domain wave mixing in the same spatial coordinate, thereby alleviating the spatial chirping and allowing high efficient optical nonlinear process. In addition, we will study improving the conversion efficiency by developing novel artificial nonlinear dielectric microstructures as discussed in the next section.

2.1.3 Design and fabrication of nonlinear artificial dielectrics to increase optical nonlinearity for spatio-temporal nonlinear processing.

Currently, there are two new techniques that can help to achieve this objective of increasing the conversion efficiency:

(i) The first technique uses periodically poled nonlinear crystals (e.g., $LiNbO_3$) to create a quasi-phase-matched condition for second harmonic generation over a long interaction length.[38-40] A quasi-phase-matching condition can be satisfied for a much longer interaction length in a nonlinear optical three wave mixing by flipping periodically the domain polarity of the bulk LiNbO3 with periodicity matching the coherence length. As a result the quasi-phase matching causes an increase in the effective interaction length resulting in a dramatic improvement in the conversion efficiency. This technique has been demonstrated to produce very high efficiency for three-wave mixing for frequency-doubling, sum-frequency generation, and difference frequency mixing.

(ii) The second technique is based on enhancing optical nonlinearity by using microstructured composite nonlinear optical materials.[41-42] The composite material is formed by combining into one system two or more optical nonlinear and/or linear materials using periodic microstructures (e.g., multilayers, grating structures, etc.). The periodicity in such composite materials is much less than the wavelength of the radiation, such that the material behavior is similar to that of a bulk material, but, with its optical properties far different from any of its constitute components. With proper design of the structure geometry, the optical nonlinearity of the composite material can be enhanced. About one order of magnitude enhancement is expected over the nonlinearities of the constituent materials.[42] The enhancement is due to the local field effects, which can be understood as a local field concentration resulting from the index periodicity of the structure. We are confident that both of these new techniques can help improving the conversion efficiency of our UCIP system.

In the second part of the proposed work, we will focus on using new techniques to increase the conversion efficiency of our spatio-temporal processors (e.g., PSM and SPD). Currently, there are two new promising approaches to increase the efficiency of optical nonlinear processes: (i) employ periodically poled nonlinear crystals to achieve quasi-phase matching for nonlinear processing,[38-40] and (ii) employ composite nonlinear materials.[41-42] The first approach solves the problem of the phase mismatch (i.e., refractive index mismatch) between the fields involved in the nonlinear processes. For example, in the second harmonic generation process that we used for our UPIC system the phase-matching condition is determined by the difference in the refractive indices between the fundamental frequency field and the second harmonic field. This refractive index difference causes dephasing between the two fields when they propagate within the material, and thus result in a periodic change of the conversion efficiency. There exist approaches that utilize material birefringence to minimize this dephasing effect (e.g., type I or II phase-matching condition). In contrast to the phase matching based on material birefringence, a new technique have been developed based on quasi-phase-matching approach. This approach enables access to the larger second harmonic coefficients and simultaneously satisfies the phase matching condition, providing more efficient nonlinear wave mixing. For example, in LiNbO3, the quasi-phase-matching approach has been found to be far superior in efficiency (e.g., about 20 times) than birefringence-based phase matching due to the ability to access a large d_{33} nonlinear coefficient as compared to d_{31} which is commonly accessed in wave mixing with birefringence-based phase-matching.[38] Composite nonlinear materials are formed by alternating deposition of two or more nonlinear materials in a multilayer structure configuration. Because the periodicity of layered structure can be made much smaller than the wavelength of the optical radiation, the composite material can act similar to a bulk nonlinear material. Recent studies have shown that such a composite nonlinear material can possess effective nonlinearity much larger than that of its constituent components. One explanation for this nonlinearity enhancement is that the local field effects within the multilayer microstructure cause a larger energy concentration of the interacting electromagnetic waves within certain regions of such composite materials and thereby effectively increase the overall nonlinearity of the material.[41] These studies have shown that such local field effects can be tailored by controlling the structure geometry and material composition of the microstructure.[42]

The phase matching condition depends on the first order dielectric constants of the optical material, while the effective optical nonlinearity of a composite material is determined by both first order as well as higher order dielectric properties of the materials. Since we can achieve specific dielectric properties by designing artificial dielectric microstructures composed of several different materials (linear and/or nonlinear), it will be possible to design an artificial nonlinear material that can simultaneously satisfy the phase matching condition and provide enhancement of the optical nonlinearity (similar to that of a composite material). During the last few years we have been studying artificial dielectric materials that are made of subwavelength periodic composite dielectric materials. We have found several unique properties in such artificial dielectric materials, including form birefringence[43,44] and anisotropic spectral reflectivity.[45,46] We also found that we can synthesize an artificial dielectric material with the desired polarization properties by appropriate design of the material composition.[43] To carry out these studies we have developed numerical modeling tools[43,47] (based on rigorous coupled-wave analysis and finite-element analysis) and various fabrication procedures.[44,46] With these modeling tools and fabrication techniques we constructed unique polarization devices, including dielectric polarizers, retardation plates, and polarizing beamsplitters based on a multilayer subwavelength grating structure. The beam splitter has demonstrated a very high polarization extinction ratio for a large incidence angular bandwidth and for wide wavelength range radiation. Based on our past experience, we propose to design a new nonlinear artificial dielectric material employing a 2-D or a 3-D periodic structure instead of the 1-D layered structure that has already been demonstrated[41,42]. Such design approach introduces additional degrees-of-freedom which can be used to tailor values of both the linear and the nonlinear dielectric constants to meet the efficient wave mixing requirements. To find an analytical solution for such a 2-D or a 3-D structure will be very difficult if not impossible. Therefore, it is necessary to develop new modeling techniques for design and characterization of such nonlinear artificial dielectric microstructures. We will use the microfabrication techniques to realize such nonlinear microstructures and test them in our nonlinear wave mixing experiments. The fabrication of such composite structures will use RF magnetron sputtering System. Subwavelength nanostructures will be fabricated using e-beam lithography and reactive ion beam etching techniques.

2.1.4 PSM and SPD fiber-optic communication link

In addition to the investigation of the PSM and the SPD devices we also propose to investigate the effects of the communication channel on the transmitted signal fidelity. We propose to construct a fiber optic link between a TDM multiplexer and demultiplexer and characterize such a link performances in terms of efficiency, speed, signal fidelity, synchronization, nonlinear fiber dispersion and its compensation, and the effect of fiber optic amplifiers. The proposed communication systems related research will be carried out in coordination and collaboration with the optical communications and networks researchers at JPL led by Dr. L. Bergman and Dr. J. Lesh. We will also explore the possibility of demonstrating and testing our developed technology in a practical optical communication and network environment with JPL.

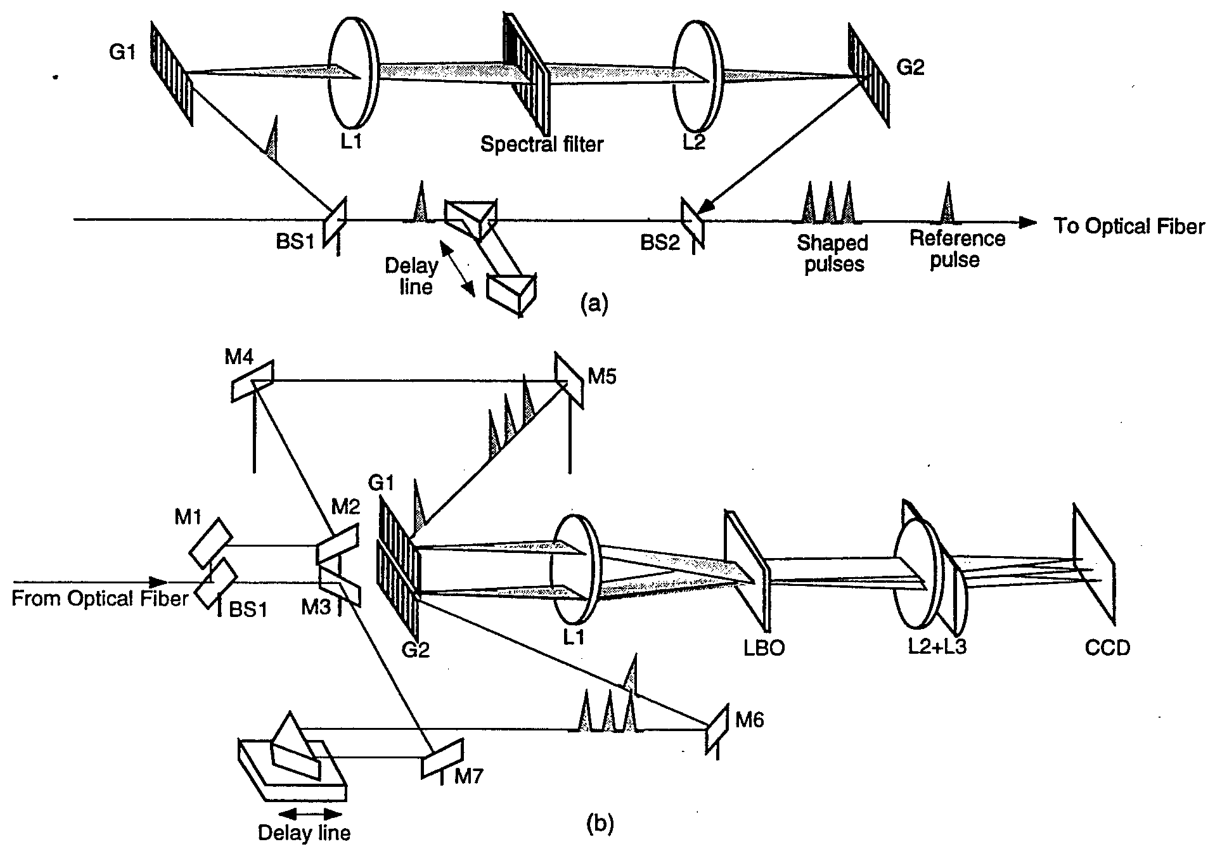

Fig. 4. Schematic diagram of optical processors for imaging through a single mode fiber: (a) a pulse shaper and (b) a pulse imager.

For example, synchronization between the transmitter and the receiver is very critical in a high speed communication channel, . In order for PSM and SPD to be implemented for ultra-high speed communication, the two systems have to be synchronized with an accuracy finer than the bit rate of the signals, corresponding to time resolution shorter than a picosecond. In the initial experiments we have demonstrated all optical parallel signal transmission through a single mode fiber with our SPD technique.[48] With our approach we sent a reference pulse along with the shaped pulse through a single-mode optical fiber where two pulses are separated by time-division (see Fig. 4). Therefore, the two pulses could acquire identical linear dispersion upon propagation through the fiber. Such group dispersion can be compensated either with a pulse shaper at the receiver, or within the pulse imaging system. The uniqueness of our approach is that the system is self-referenced, alleviating the requirement of synchronization between the transmitter and the receiver.

As a part of this study we also propose to investigate the effect of fiber-optic amplifiers on the short pulse signal fidelity. Nonlinear propagation such as the soliton propagation in an optical fiber become relevant in optical communication systems when high peak power femtosecond pulses are used. Such nonlinear propagation can produce frequency expansion and modulation of the short pulses, which could affect the serial-to-parallel conversion by the SPD system. A passive technique to avoid the nonlinear dispersion is to reduce the peak power by chirping the optical pulses before sending them into the fiber, and re-compressing the beam at the receiver before introducing it into the SPD device. For developing active techniques to compensate for the nonlinear dispersion in the fiber we will need to investigate the nonlinear propagation of femtosecond pulses. For example, for soliton propagation, the short pulse will experience self phase modulation to maintain its temporal profile. Therefore, we anticipate that the output pulse from the fiber will have the same shape as the incident pulse but with a wider spectral bandwidth, that can rise to a shorter corresponding transform limited pulse. We anticipate that such propagation effects will have very little negative, if not positive influence on the performance of our SPD system. For example, if the pulses introduced into the SPD system are self phase modulated with a quadratic chirp, the generated second harmonic field spatial image will appear super-resolved, which may be useful in increasing the SNR.

2.1.5 Additional Research Projects

The requested equipment will also enhance experimental work on other integral parts of the FRI Photonic Imaging Network project as well as the proposed BMDO and AFOSR projects on nonlinear spatio-temporal processing of femtosecond pulses. These include measuring phase and amplitude of the spectral components of short pulses, characterization of nonlinear optical and electronic properties of semiconductors and semiconductor microstructures, quantum and classical cryptography, and transparent optical networks.

We propose to investigate two photon interference using a parametric down-conversion source with the signal and the idler photons launched into two separate channels containing Mach-Zehnder interferometers that use frequency division long distance interferometers. We also propose to experimentally demonstrate and evaluate the frequency division long distance interferometer using dichromatic interferometric beamsplitter built of unbalanced Mach-Zehnder interferometers. The proposed quantum cryptosystems will be evaluated in terms of probability of successful eavesdropping in a single physical link environment, considering issues involved in a practical optical link. Various eavesdropping strategies depending on a specific long distance interferometry method will also be modeled, analyzed and compared.

The proposed classical encryption methods will be investigated in conjunction with the ultrahigh bandwidth of ultra-short laser pulses in third generation optical networks. The frequency spectra of an ultra-short pulse, phase-encoded by a phase-only computer-generated-hologram, or changed dynamically via four-wave spectral domain mixing processes, occupies a large bandwidth. Thus, little power appears at any given frequency band or over any short sub-interval of time and secure communications can be carried out just as in traditional spread spectrum systems. In addition, the proposed classical encoding of ultra-short information carrying pulses will be realized for implementing secret key established via symmetric, public-key and quantum cryptosystems. The security and privacy performances will be evaluated, analyzed and compared.

Femtosecond pulses are too short to be resolved by electronic detectors. Indirect measurements of such pulses are usually performed by recording the optical auto-correlation traces or the cross-correlation traces with a short reference pulse, through a nonlinear interaction of optical fields in a second harmonic generation process. This time domain measurement technique provides information only about the intensity variation of the interacting fields, whereas the phase information cannot be recovered. However, the complete information on the phase and amplitude of the spectral components of the two pulses is contained in the intensity distribution of the interference pattern. We will employ the methods of electronic holography to detect the resulting interference pattern, and extract the amplitude and the phase information by transforming the digitized data with a computer. Since the time variation of the signal pulse can be calculated from the measured spectral interference, no nonlinear techniques are needed, and therefore it is expected that this technique will be more sensitive then the currently employed second harmonic generation method. The results of these study are important for development of detection for robust quantum cryptosystems.

2.1.6 Impact of the proposed research

The proposed research will further advance the technology and the fundamental understanding of the nonlinear optics of ultrashort pulses in conjunction with ultrahigh bandwidth communication applications. We anticipate that the proposed research will significantly advance and impact the development of such unique devices and systems as PSM, SPD, as well as communication system built of PSM and SPD communicating via fiber-optic and/or free-space channel. The results of the proposed research will also significantly advance the design and fabrication of nonlinear artificial dielectric materials that utilize near field effects to increase their efficiency. The collaborative effort between the UCSD and the SRI teams will also explore and advance the application of spectral hole burning materials for efficient spectral domain wave mixing for communication applications.

The proposed research will also provide optical communication system related results on the effects of the fiber optic and/or free space communication channel on the signal fidelity, including the effects of linear and nonlinear dispersion and its compensation, the effects of fiber optic amplifiers, etc. The proposed communication systems related research will be carried out in coordination and collaboration with the optical communications and networks researchers at JPL led by Dr. L. Bergman and Dr. J. Lesh, and include the possibility of demonstrating and testing of our technology in a practical network environment. In addition, the proposed research on spatio-temporal signal processing technology development will also have a significant impact on other science and engineering areas that use ultrashort laser sources, including medical and biomedical imaging, chemistry and physics.

The proposed work, executed in the Department of Electrical and Computer Engineering at the University of California, San Diego will also have a strong impact on the education of students at the graduate and undergraduate levels. The students involved in this research will bring to it their knowledge in the areas of optics, electromagnetic wave propagation, nonlinear optical material science, and computer engineering, which will be useful for carrying out the proposed work. They will gain extensive first-hand experience in the growing field of optoelectronics in general and in ultrafast optical signal and information processing in particular. The students knowledge will be further enhanced through special courses and seminars related to the proposed subject. We expect that the unique background of our students will be an important factor in the introduction and efficient integration of the advances in optoelectronic technology for high performance computing and communication into U.S. industry.

2.1.7 References

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2.2 Supporting Facilities at UCSD

The Department of Electrical and Computer Engineering at the University of California at San Diego is housed within two large modern structures - Engineering Building Unit 1 (EBU1) and Engineering Building Unit II (EBU II). The facilities available for this effort are grouped into several major categories:

Device Processing

Several class 100 clean rooms are located in the Engineering Building at UCSD, one of which is dedicated to the fabrication of optoelectronic devices. A Cambridge EBMF 10.5 electron-beam lithography system is available for fine-line lithography and microfabrication. Several computer aided design stations for mask design are in operation. In addition, standard semiconductor fabrication equipment is available. The equipment includes a plasma-enhanced CVD reactor, a reactive ion etcher, ion-beam mill, mask aligners, an ion implanter, diffusion furnaces, electron-beam evaporators, thermal evaporators and RF and magnetron sputter systems. Device packaging facilities include a metal plating bath, a thermo-sonic compression wedge bonder, and a die bonder.

Optical Signal Processing and Device Characterization

The Optical Information Processing Laboratory is equipped with complementary equipment required to carry out this project. For instance, optical tables, CW Ti:sapphire and argon-ion lasers, tunable femtosecond lasers, He-Ne lasers, and other basic optical and electro-optic components are available. The optical equipment is interfaced with Pentium-based PC with video boards and a SUN workstation. Code-V, a state-of-the-art optical system computer-aided-design program, is available.

Electrical Device Characterization:

Extensive device characterization facilities are available, including the following: complete DC electrical device characterization from ~10K to 300°C using HP 4145B, 4155A, and 4156A semiconductor parameter analyzers; frequency-dependent and temperature-dependent (~10K to 300°C) capacitance-voltage spectroscopy; admittance spectroscopy; multiple low-temperature device characterization stations; temperature-dependent Hall effect characterization; magnetotransport measurements in magnetic fields up to 8 T; and extensive optical and electro-optical characterization facilities.

Advanced Materials Characterization:

State-of-the-art facilities are available for advanced materials characterization, including the following: high-resolution transmission electron microscopy; scanning electron microscopy; high-resolution x-ray diffraction; MeV ion backscattering spectrometry facility for Rutherford backscattering and channeling studies; ultrahigh vacuum scanning tunneling microscopy; and atomic force microscopy and related scanning probe techniques.

Networks and Communications Simulations

Communication networks laboratories are located in EBU I and EBU II. Currently available are several networked Sun workstations. We have several licenses for OPNET network simulation software, a state-of-the-art computer-aided simulation environment. Two HP LAN protocol analyzers have recently been acquired. Recently, the equipment in this laboratory has been enhanced by equipment grant of over $300,000 from Hewlett Packard including BER testing and workstations. We are in the process of establishing a fiber connection to the optics laboratory providing the hardware infrastructure for the wavelength division multiplexing of standard ATM with that of the ultra-high speed optical networks described in this proposal.

2.3 Requested Equipment Justification

Ultrafast Spectrum Analyser, Diagnostic B, Spectra Physics, Single Shot Autocorrelator, Model SSA-F, Spectra Physics, and Oscilloscope, Tektronix Model TDS-640A are requested for diagnostics and analysis of the spectral bandwidth of the tunable femtosecond laser system that will be used in our SPD, PSM, and optical communication link. Scanning Autocorrelator, LZF-0198, Inrad Inc. is requested to characterize the shape of the pulses generate in PSM. Mach-Zender Optical Modulator,10-150-1-3-C1-AP, UTP, Amplifier, 20T4G18, Amplifier Research, and the Signal Generator, HP 83732B, HP are requested to implement the PSM for optical communication link. Photodetector, 1014, New Focus Inc. and Digital Oscilloscope, HP 54750A and HP 54752A are requested to implement the SPD of the optical communication link. RF Magnetron Sputtering System that will be built of components listed below (see budget item # 11 (a) through (d)) is requested for fabrication of composite nonlinear optical materials. Data acquisition and laboratory controller (Pentium with interfaces and accessories) IBM, is requested to interface and control the electronic and electrooptic components of the experiments on implementing parallel-to-serial and serial-to-parallel optical multiplexers.

2.4 Description of the proposed research support facilitated by the instrumentation

The requested equipment and instrumentation will facilitate the research on transparent ultra-high speed optical networks and the development of the underlying technologies currently being funded by BMDO, AFOSR, ARPA-OTC II, and NSF. The requested equipment and instrumentation will also enhance the currently funded research program on "Photonic Imaging Networks" at the University of California, San Diego, supported by the DOD's Focused Research Initiative (FRI) Program of BMDO via AFOSR. This program is focused on optical fiber communication networks with special emphasis on transmission of images and image-format information utilizing the ultrahigh optical fiber bandwidth (e.g., over 1 Tbits/sec) by exploiting unique properties of femtosecond laser pulses. In particular, this novel approach will be investigated in conjunction with basic research on devices and optical network systems for enhanced information transmission rate, network controllability and reliability as well as network security and privacy utilizing methods of quantum and classical cryptography. This proposal is a collaborative effort between nine faculty and five research assistants from UCSD including a Russian scientist from Vavilov Institute, St. Petersburg. Additionally, the requested equipment will be used in our currently funded project on "Quantum and Classical Cryptography for Security and Privacy of Photonic Networks," and the currently proposed project on "Nonlinear Spatio-Temporal Processing of Femtosecond Pulses for Ultrahigh Bandwidth Communication." In this project we will investigate the effects of the fiber optic and/or free space communication channel on the signal fidelity, including the effects of linear and nonlinear dispersion and its compensation, the effects of fiber optic amplifiers, etc. In addition, the requested equipment and instrumentation will provide the necessary tools to enhance the ongoing research program on composite and artificial optical materials research on diffractive optics with multifunctionality and programmability. This research project is currently supported in part by the NSF, ARPA-OTC II and AFOSR.

2.5 Description of the effect of the instrumentation on the training of the future scientists and engineers.

The FRI Project on Photonic Imaging Networks has been established in the Department of Electrical and Computer Engineering at UCSD. The proposed studies will advance the basic science and engineering of space-time fields and processing, including the investigation of the interface between quantum and classical optics. The studies in ultrashort pulse propagation and measurements of femtosecond pulse amplitude and phase will lead to better understanding the propagation of transient electromagnetic waves in both linear and nonlinear media. The research in ultrashort pulses, quantum and classical optical cryptography, dynamic nonlinear spectral wave-mixing, and nonlinear artificial dielectric materials will form the basis required for the development of practical ultrashort pulse systems that will be needed for the next generation of photonic imaging networks.

The proposed work, executed in the Department of Electrical and Computer Engineering at the University of California, San Diego will also have a unique impact on the education of students at the graduate and undergraduate levels. The students involved in this research will bring to it their knowledge in the areas of optics, electromagnetic wave propagation, material science, nonlinear optics, quantum measurements, network theory, communication theory, and computer engineering. They will gain extensive first-hand experience in the growing field of photonics in general and in complex space-time optical information processing, quantum cryptography, communication theory of photonic networks in particular. The students background will be further enhanced through special courses and seminars related to the proposed subject. We expect that the unique background of our students will be an important factor in the introduction and efficient integration of the advances in photonics technology for high performance computing and communication into U.S. industry.

2.6 Equipment Installation

The requested equipment will be installed in the existing space of the Optical Information Processing Laboratory (EBU-1, rooms B517, B519, and B521), the communication network laboratories (rooms 4702, 4703 EBU I and in EBU II), and in the Central Fabrication Facility (1702-1720 EBU1) operated by the Department of Electrical and Computer Engineering at UCSD. All the necessary utilities (electrical, chilled water, etc.) are available in the laboratory and no additional funding for installation will be required.

2.7 Equipment life

The requested equipment is based on solid state technology and thereby a long (5-10 years) lifetime is expected. Maintenance contract for the requested equipment will be made.

2.8 Equipment Maintenance Plan

Since the requested equipment will be used for a variety of research projects on optical networks as well as for graduate teaching, it will be maintained from the resources supporting this program. Currently funded and pending projects (e.g., BMDO, AFOSR, NSF, NRAD, ARPA-OTCII) will contribute to the maintenance of the requested equipment. The principal investigators will be primarily responsible for the maintenance and the management of the equipment.