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(54) **ULTRA-MINIATURIZED THZ COMMUNICATION DEVICE AND SYSTEM**

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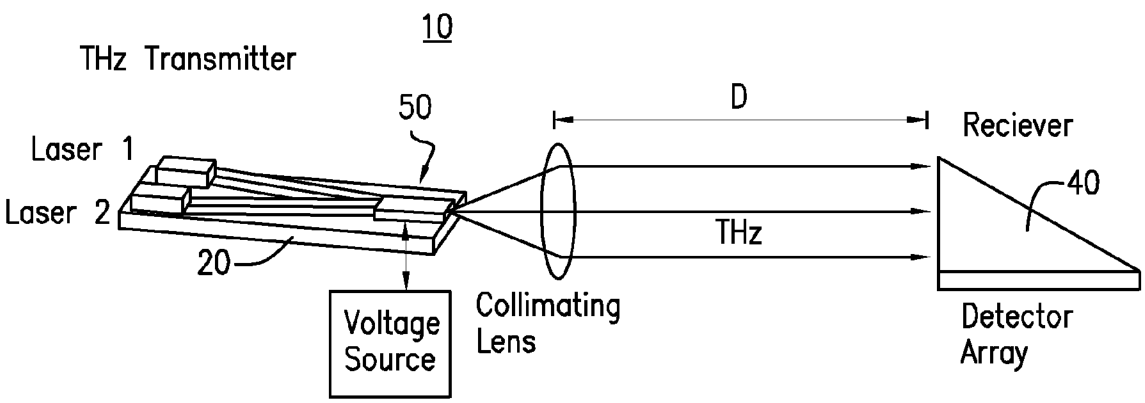
(57) **ABSTRACT**

Ultra-miniaturized THz spectrometer/multi-channel receiver devices are provided. THz communication devices employ a THz transmitter, a THz receiver and a modulator, wherein the THz transmitter is configured to introduce a THz signal to the modulator and the THz receiver is configured to receive the THz signal from the modulator and demodulate the signal. Communication systems and methods employing the THz spectrometer/multi-channel receiver devices enable secure communications. Portable THz emitter devices are provided employing semiconductor lasers and a nonlinear birefringent waveguide monolithically integrated on the same substrate.



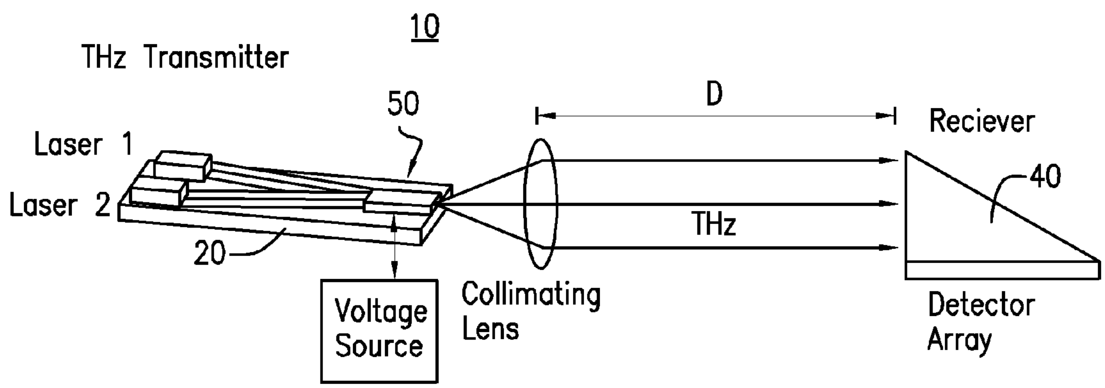

10
THz Transmitter
50
D
Reciever
Laser 1
40
Laser 2
THz
20
Voltage Source
Collimating Lens
Detector Array

FIG. 1

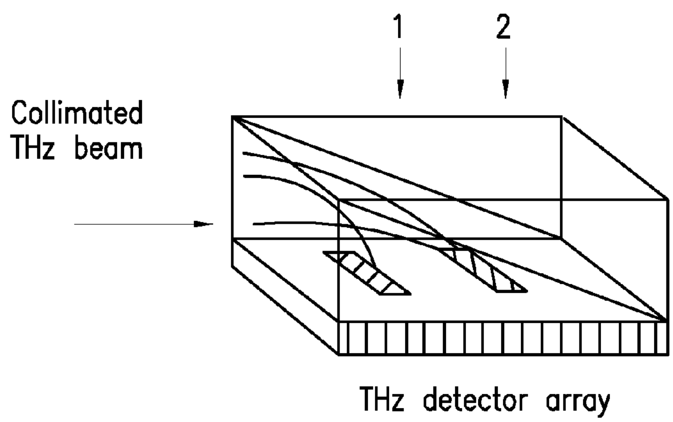

1
2
Collimated THz beam
THz detector array

FIG. 2

Talbot Self-imaging

Transverse Bragg Waveguide

- Periodic in transverse direction
- Controllable by variation of period Λ
- Controllable by variation of Δn

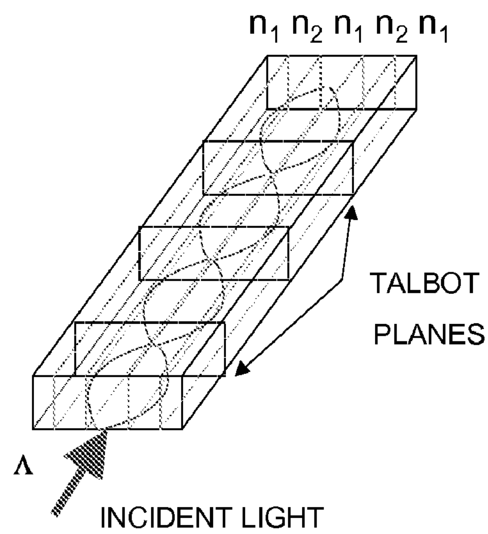


FIG 3

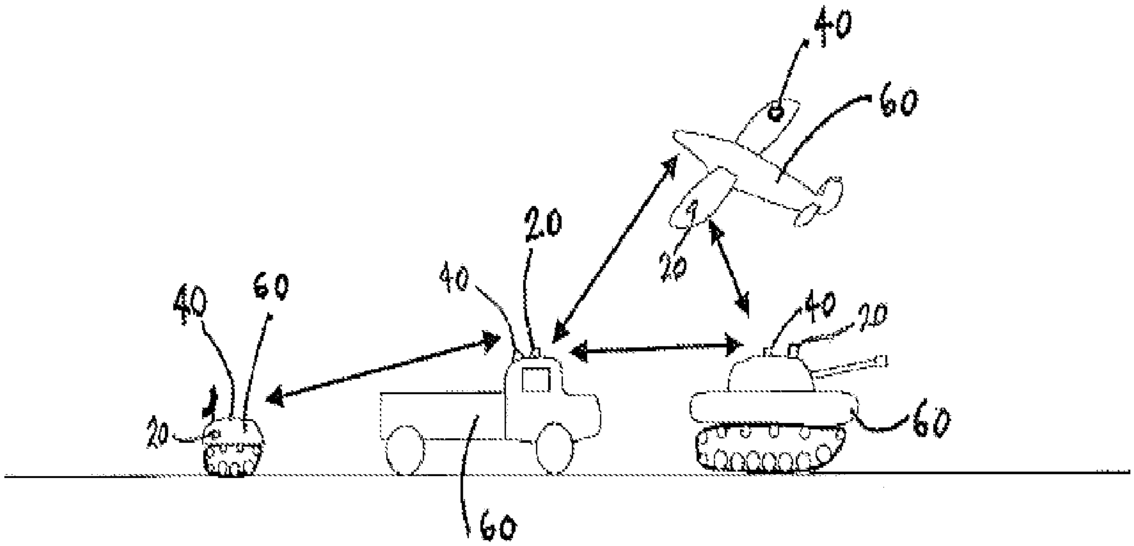


FIG. 4

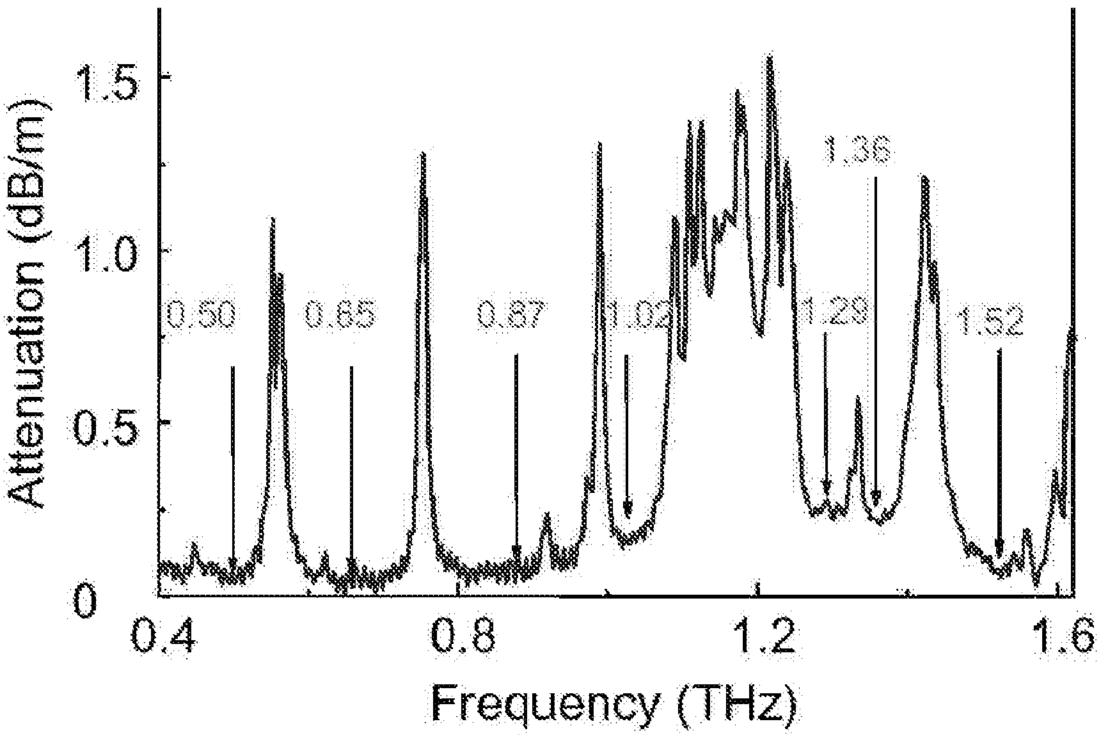

Attenuation (dB/m)
1.5
1.0
0.5
0
0.4
0.8
1.2
1.6
Frequency (THz)
0.50
0.65
0.87
1.02
1.29
1.36
1.52

FIG 5

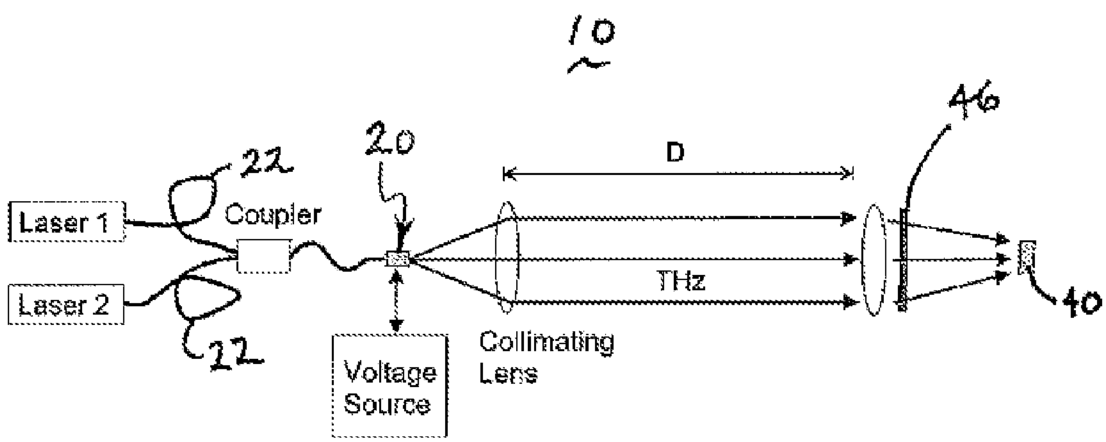

10
Laser 1
Laser 2
22
22
Coupler
20
Voltage Source
Collimating Lens
D
THz
46
40

FIG. 6

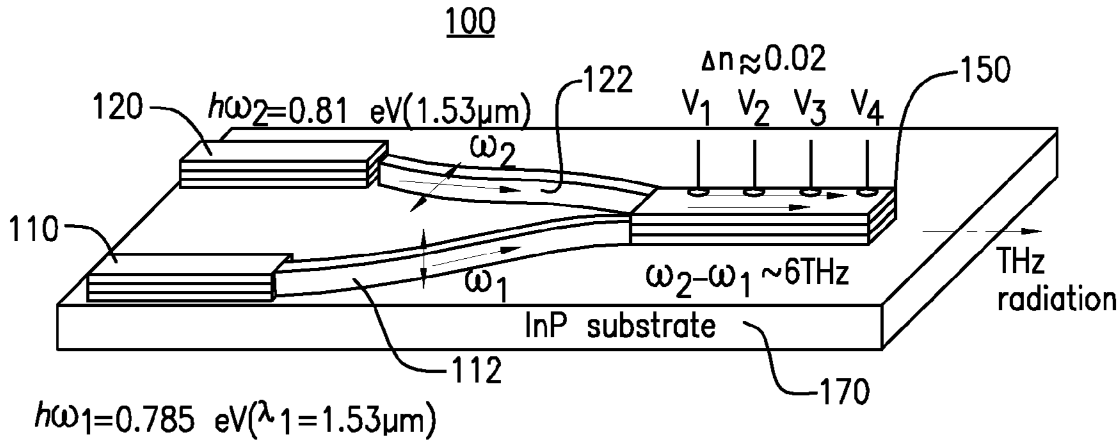

100
Δn≈0.02
122
150
120
hω2=0.81 eV(1.53μm)
V1 V2 V3 V4
ω2
110
ω1
ω2-ω1 ~6THz
THz
radiation
InP substrate
112
170
hω1=0.785 eV(λ1=1.53μm)

FIG. 7

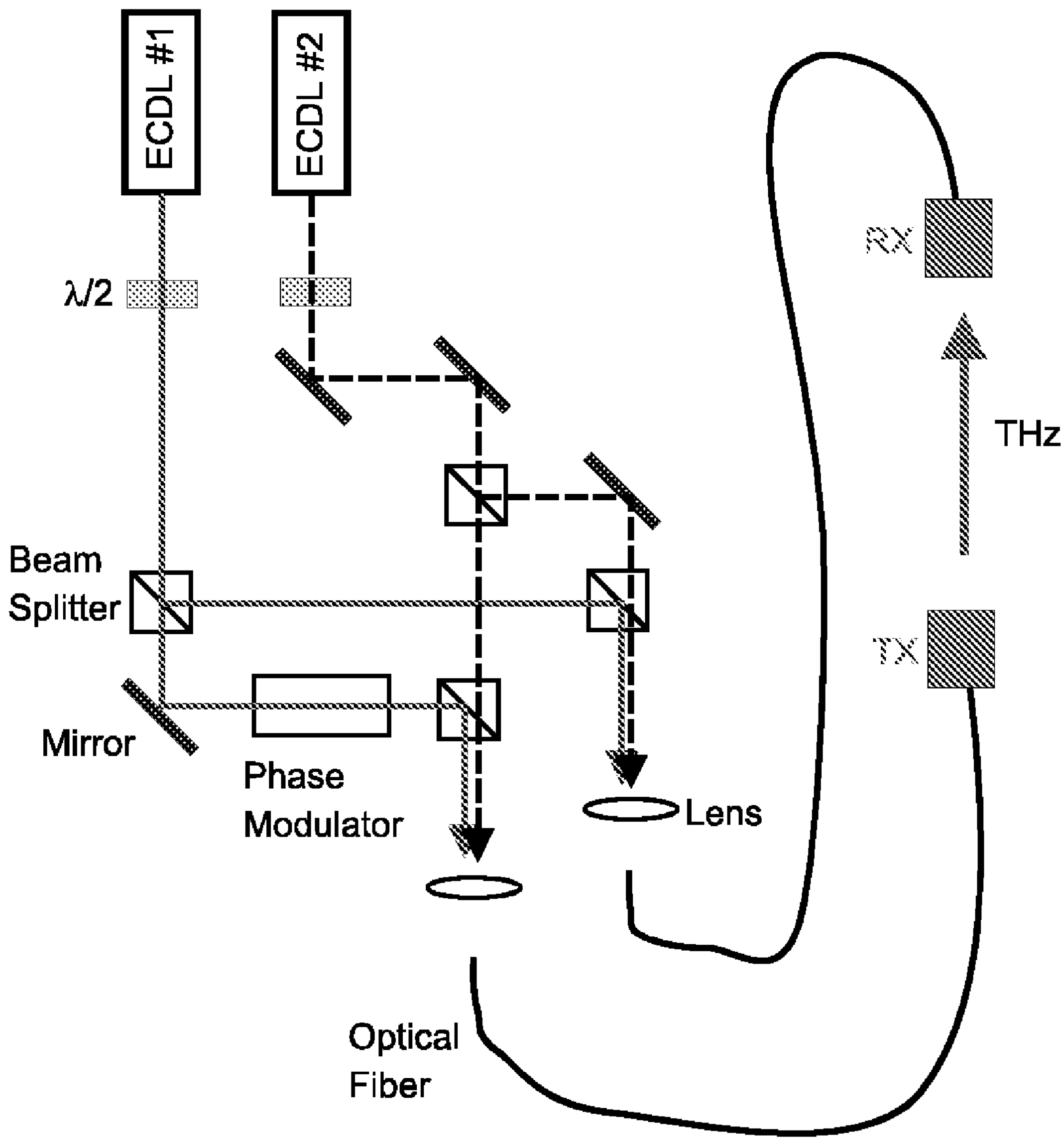

ECDL #1
ECDL #2
λ/2
RX
THz
TX
Beam Splitter
Mirror
Phase Modulator
Lens
Optical Fiber

FIG. 8

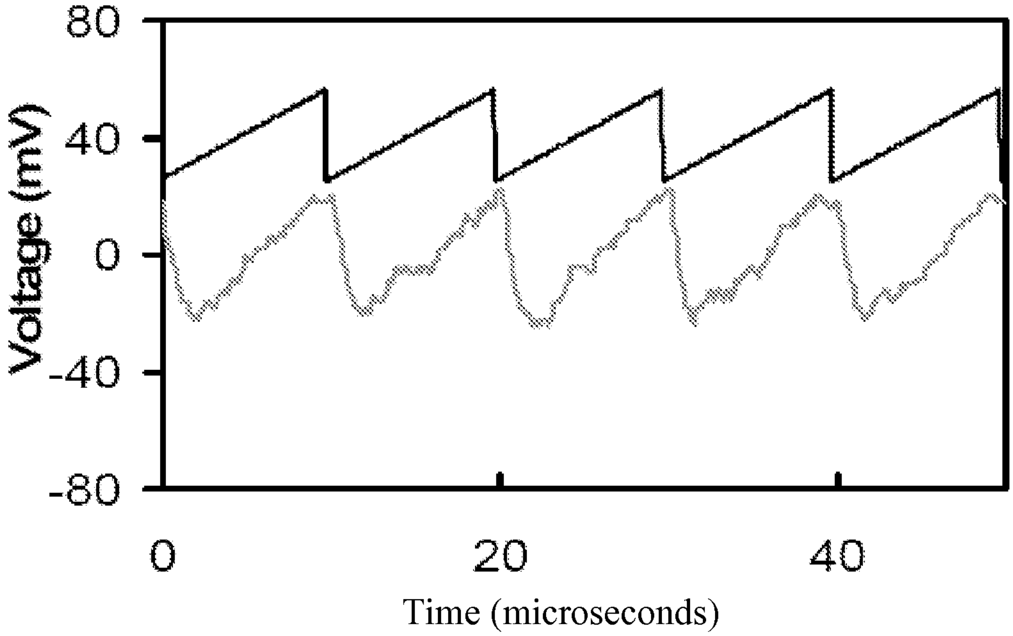

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9A

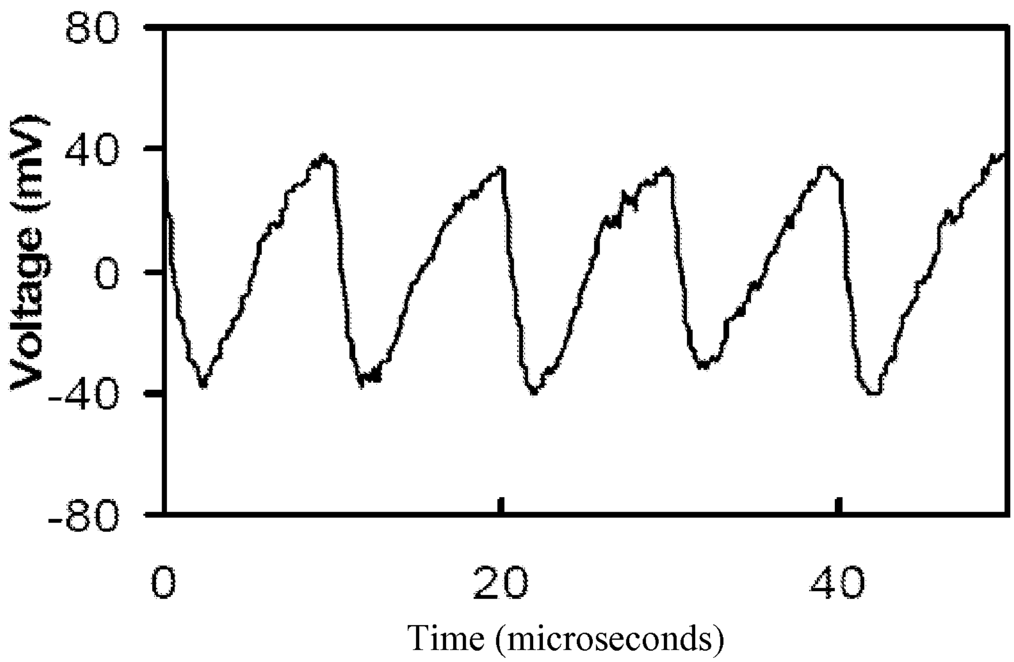
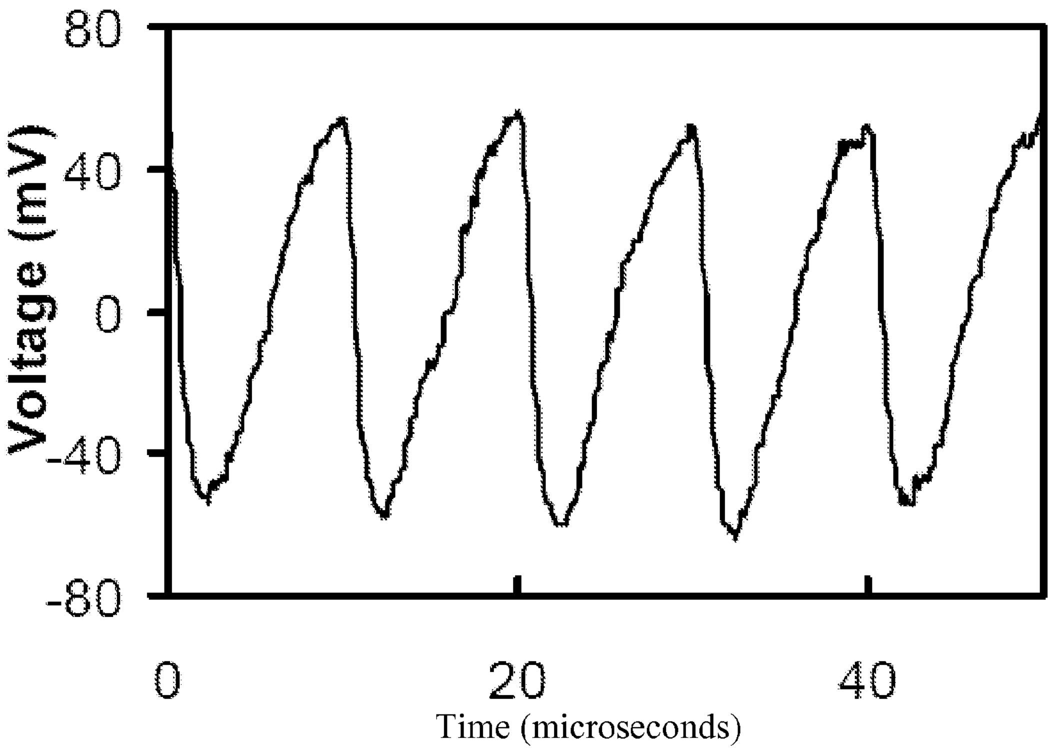
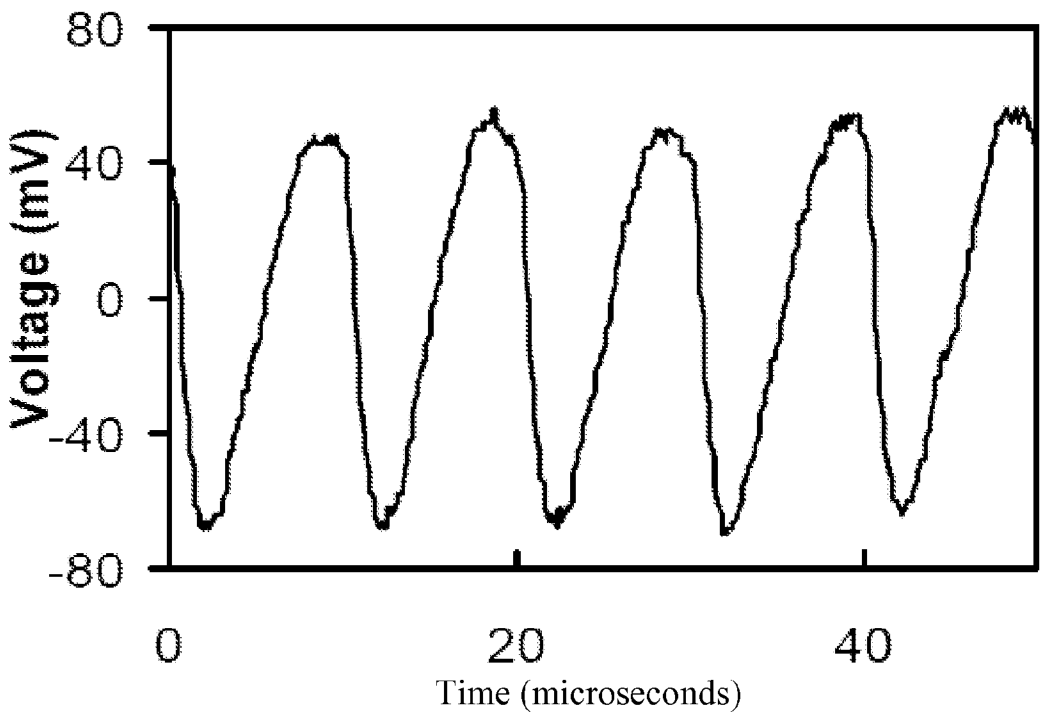

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9B



80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9C



80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9D

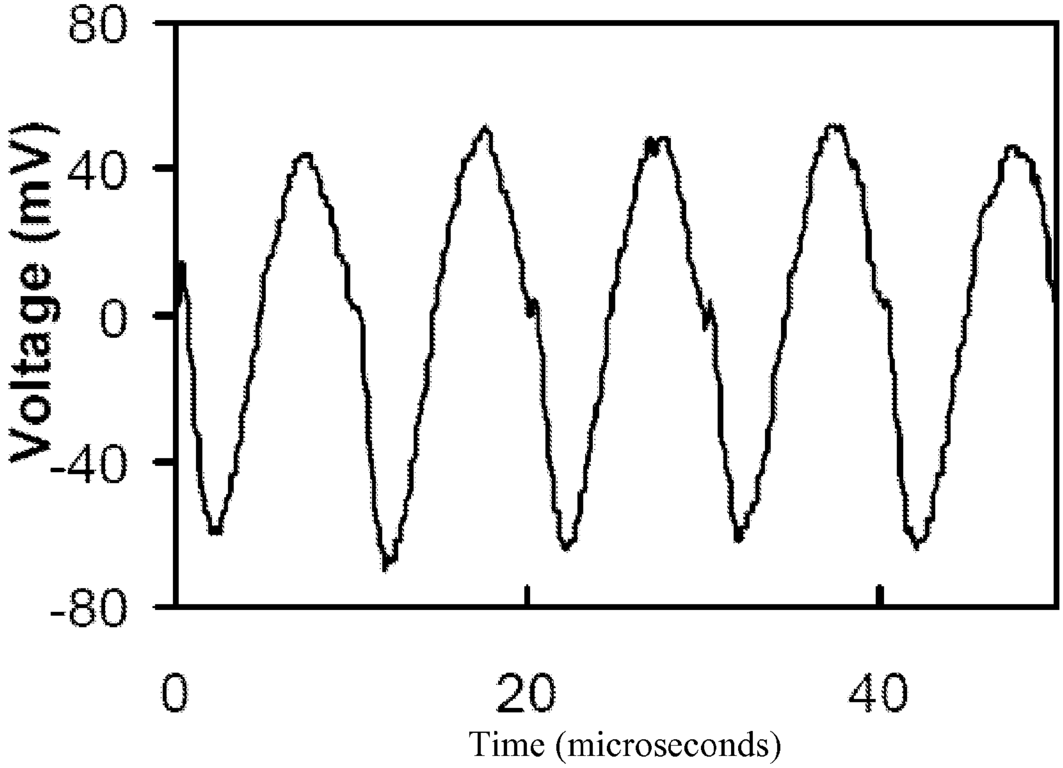

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9E

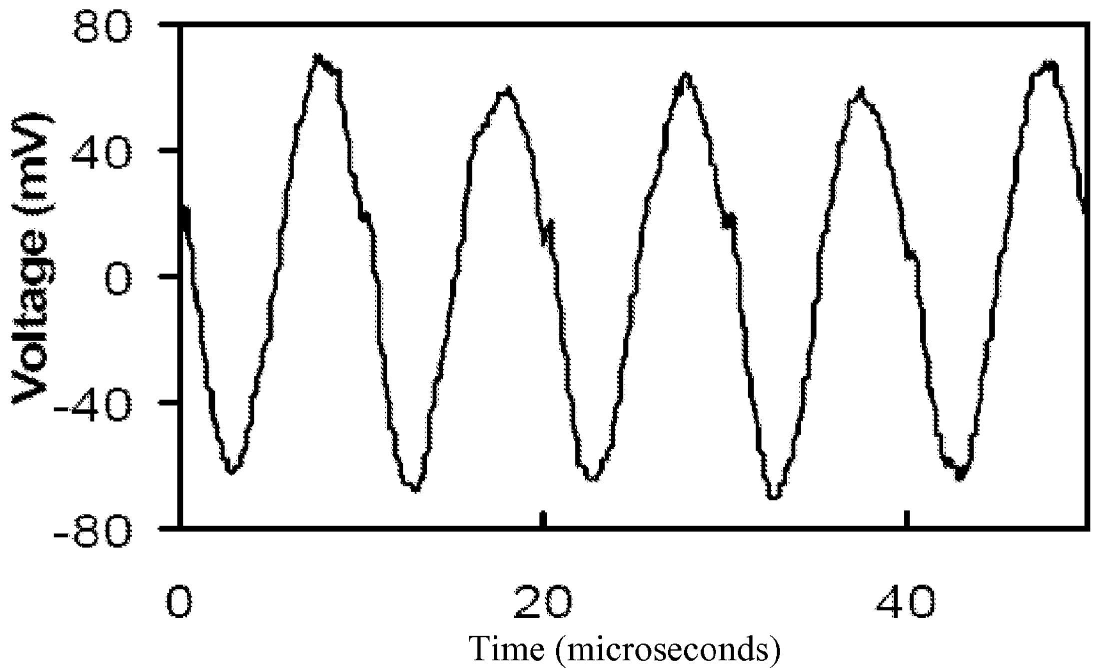

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9F

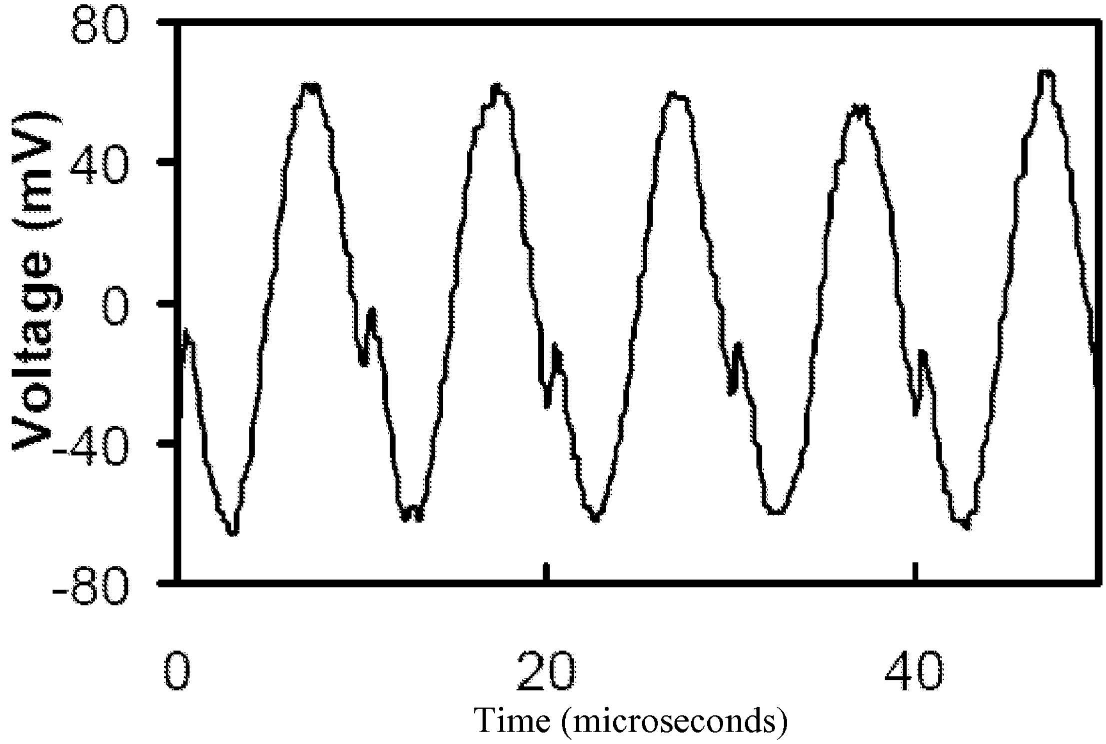

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9G

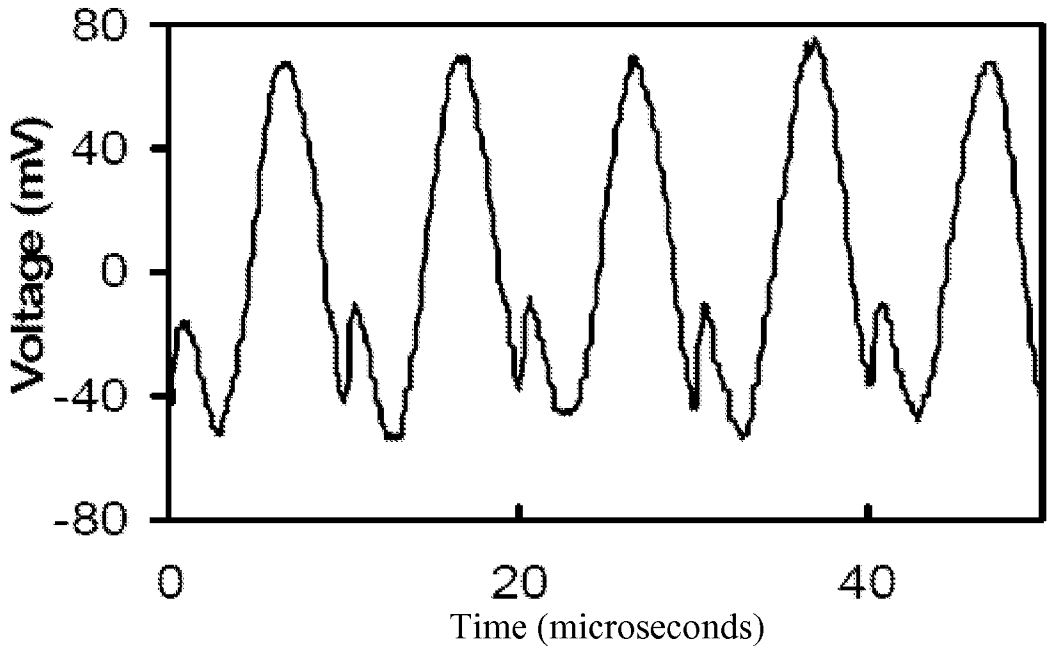

80
40
0
-40
-80
Voltage (mV)
0
20
40
Time (microseconds)

FIG. 9H

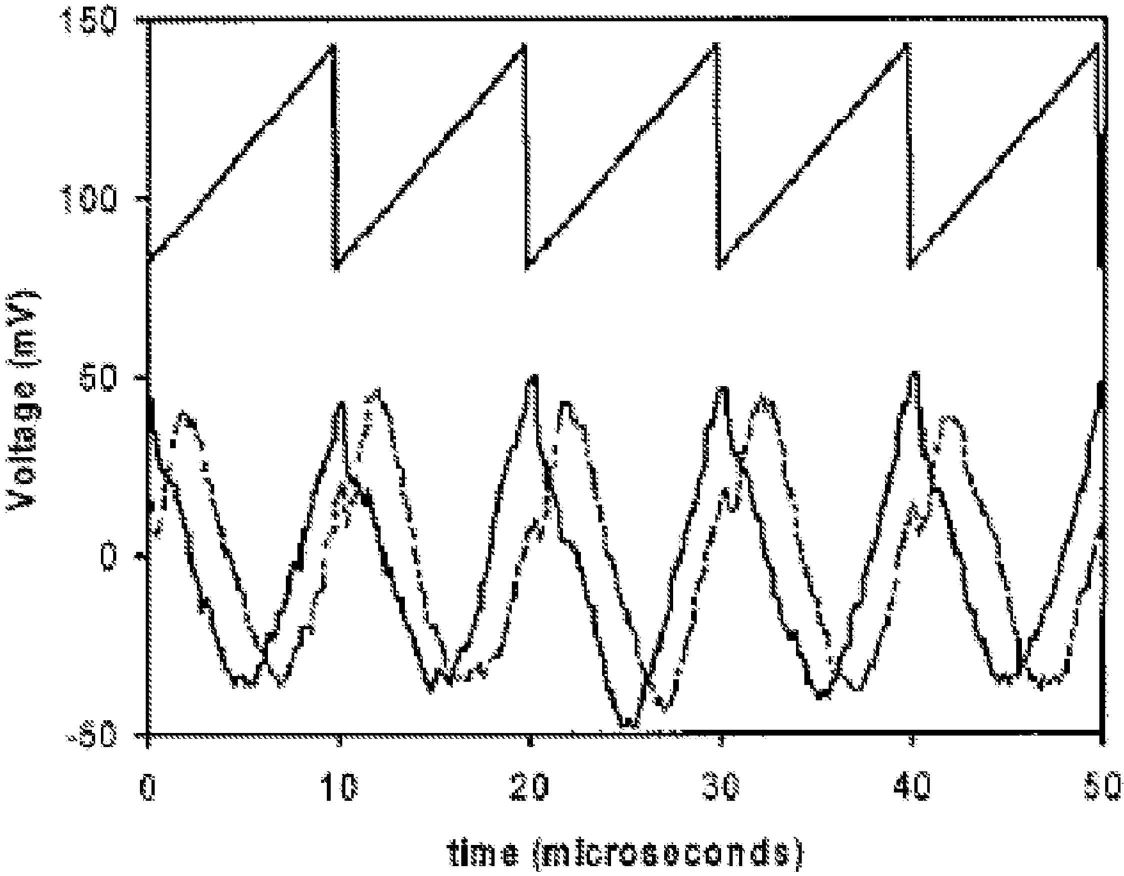


FIG 10

ULTRA-MINIATURIZED THZ COMMUNICATION DEVICE AND SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Nos. 61/046,126, filed Apr. 18, 2008, 61/046,132, filed Apr. 18, 2008 and 61/051,887, filed May 9, 2008, the entireties of which are incorporated herein by reference.

GOVERNMENT RIGHTS

[0002] The research leading to the present invention was supported, in part by the Department of Defense's Technical Service Work Group (TSWG) through a contract (N41756-04-C-4163) and by the U.S. Army through a contract (DAAE3003D1015-18). Accordingly, the United States Government may have certain rights in the invention.

FIELD OF THE INVENTION

[0003] This invention relates to terahertz (THz) communication devices and systems and methods of using same.

BACKGROUND OF THE INVENTION

[0004] There has been a rapid expansion in the area of terahertz technology, apparatus and components using THz technology. Commensurate with this expansion is the need for smaller, faster, less expensive and more reliable THz components. THz applications include secure wireless communications, stand-off detection of explosives, biological weapons, chemical weapons, hand-held scanners, and non-destructive testing.

[0005] In the development of future combat systems, vehicles must be lighter, faster, and consequently not as heavily armored. Communications between vehicles must be stealthy so that hostile forces can not identify the presence nor mission objectives via eavesdropping on communication channels. Unmanned vehicles require short-distance secure communications links so that they can receive instructions and transmit data before dispersing to conduct their remote controlled or autonomous mission.

SUMMARY OF THE INVENTION

[0006] In accordance with at least one embodiment the present invention provides ultra-miniaturized THz spectrometer/multi-channel receiver devices.

[0007] In one embodiment an ultra-miniaturized THz spectrometer/receiver system is provided for hand-held, portable sensing, monitoring, and detection applications. In another embodiment an ultra-miniaturized THz spectrometer/receiver is employed as a multi-channel THz receiver integrated in a THz secure, wireless communications link. In another embodiment devices in accordance with the present invention may be employed as hand-held or hands-free wireless communication devices. The present inventions can be employed as next-generation wireless communication devices.

[0008] The ultra-miniaturized THz receiver can receive THz signals at several different THz frequencies (channels). The ultra-miniature size of the receiver (≦6 mm) enables the communications link to be used either with an integrated component in a communications system or with stand-alone or hand-held communications elements. Other key attributes include minimal fabrication, operational and maintenance costs of the ultra-miniaturized receiver. Since the receiver can be mass fabricated from silicon wafers using standard lithographic processing (using, for example, 10 i.tm features), the cost per receiver is relatively low. Furthermore, the lack of moving parts in the receiver minimizes the cost of fabrication and maintenance.

[0009] In one embodiment the THz receiver is based on photonic crystal structures. These structures permit the fabrication of compact, efficient, and low-cost photonic devices. The typical dimensions of the present THz receivers are comparable to only a few THz wavelengths. The present devices differ from those in the prior art at least in that they (a) are three dimensional in nature; (b) involve both passive and active elements; (c) employ imaging as well as filtering aspects; and (d) ultra-miniature receivers on the order of a few THz wavelengths are realized as the result of THz photonic crystals being integrated with THz detector elements.

[0010] In at least one embodiment a THz communication system is provided for data communication between mobile units. The use of THz radiation as a method for data communication through air is intrinsically eye-safe and presents no radiation hazards. There are no reported adverse health effects due to THz radiation.

[0011] The present designs do not require any external light sources (lasers), which are required in state-of-the-art THz emitters. This makes the present approach different from THz pulse generation with visible femtosecond laser operated at the pulse repetition rate in THz range. The present designs can use thermoelectric cooling and do not require cryogenic temperatures like most conventional Quantum Cascade Lasers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] To assist those of ordinary skill in the relevant art in making and using the subject matter hereof, reference is made to the appended drawings, wherein:

[0013] FIG. **1** depicts a diagram of a THz secure communications link in accordance with at least one embodiment of the present invention;

[0014] FIG. **2** depicts a schematic of a photonic crystal prism employed as a multi-channel receiver in accordance with at least one embodiment of the present invention;

[0015] FIG. **3** depicts a diagram of Talbot planes as realized in a (transverse) Bragg wave guide in accordance with at least one embodiment of the present invention;

[0016] FIG. **4** depicts a schematic diagram of an embodiment of a secure THz communication between manned and unmanned vehicles in accordance with at least one embodiment of the present invention;

[0017] FIG. **5** is a graphical depiction of an experimental measurement of THz attenuation through the atmosphere at a temperature of 22° C. and 8% relative humidity in accordance with at least one embodiment of the present invention;

[0018] FIG. **6** depicts a schematic breadboard model of a single channel THz secure communications link in accordance with at least one embodiment of the present invention;

[0019] FIG. **7** depicts a schematic of a portable THz emitter in accordance with at least one embodiment of the present invention;

[0020] FIG. **8** depicts a schematic diagram of fast phase modulation configuration. The half waveplates are used to rotate the polarization of the laser beams from external cavity diode laser (ECDL) 1 and 2 so that the light is polarized parallel to the polarization axis of the optical fibers.

[0021] FIGS. **9**A-**9**H are graphical depictions of THz detector voltage output versus time as a function of applied voltage to the MgO:$LiNbO_3$ modulator. Applied voltage in FIG. **9**A is 20V. The sawtooth waveform illustrates the timing of the applied voltage (not to scale) applied to the modulator relative to the THz detector output. The applied voltage increases in units of 20V with the last figure (FIG. **9**H) corresponding to 160V; and

[0022] FIG. **10** is a graphical depiction of THz detector output for a thin business card inserted (solid line) between the THz transmitter and receiver of FIG. **8** and removed (dashed curve).

[0023] It should be noted that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be construed as limiting of its scope, for the invention may admit to other equally effective embodiments. Where possible, identical reference numerals have been inserted in the figures to denote identical elements.

DETAILED DESCRIPTION OF THE INVENTION

[0024] In the following description, for purposes of explanation, specific numbers, materials and configurations are set forth in order to provide a thorough understanding of the invention. It will be apparent, however, to one having ordinary skill in the art that the invention may be practiced without these specific details. In some instances, well-known features may be omitted or simplified so as not to obscure the present invention. Furthermore, reference in the specification to phrases such as "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of phrases such as "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

[0025] Now referring to FIG. **1** a communication device **10** in accordance with the present invention includes a THz transmitter **20**, a THz receiver **40** and a modulator **50**.

[0026] A THz transmitter **20** may be selected from a GaAs photomixer or an integrated waveguide photomixer. Regarding the THz receiver **40**, if a single THz channel is required, a single THz detector (with a bandpass filter) will suffice as a receiver. For multiple channels, multiple detectors are employed with either multiple bandpass filters or other such filtering elements. A modulator **50** modulates the THz signal, modulated directly or externally to the laser, in its amplitude, frequency or phase or some combination thereof, to encode the propagating THz signal with the stream of data. Modulation methods for the transmitters are well known in the art and are described below. A demodulator "decodes" the modulated THz signal at the THz receiver **40** to retrieve the data stream.

[0027] In one embodiment a THz communications device **10** is provided having an integrated waveguide photomixer serving as a THz transmitter **20** and a photonic bandgap THz spectrometer as a multi-channel receiver **40**. A THz transmitter can be modulated (encoded with data) for example by varying the voltage across a birefringent waveguide. After transmitting through the atmosphere over a distance D on the order of at least several meters, the THz signal is detected using a THz receiver **40** as further depicted in FIG. **2**. Multi-channel operation is realized by increasing the number of THz transmitters **20** operating at distinct wavelengths (frequencies).

[0028] Now referring to FIG. **2**, a multi-channel receiver **40** may employ a photonic crystal prism. The collimated THz beam passes through a pin-hole screen **42**. It is then reflected by the upper portion of the prism and is focused onto the detector array **44**. Owing to the dispersive nature of the prism, only a specific wavelength is focused per detector-array pixel; all other wavelengths will be averaged out. Two different channels and corresponding detector arrays are shown.

[0029] Now referring to FIG. **3**, Talbot planes as realized in a (transverse) Bragg waveguide are depicted. Refractive index variations along the direction of propagation funnel the electromagnetic wave along the waveguide. See, Su Choi Tsay and H. Grebel, "Design of transverse holographic optical interconnect", *J. Appl. Optics,* 33, 6747 (1994); H. Grebel, J. L. Graziani, S. Vijayalakshmi, L. Shacklette, K. Stengel, L. Eldada, R. Norwood and J. Yardley, "Self-imaging chirp holographic optical waveguides", *Appl. Opt.,* 36, 9391 (1997); J. M. Tobias and H. Grebel, "Self-imaging in photonic crystals in a sub-wavelength range", *Opt. Letts.,* 24, 1660 (1999); J. M. Tobias; M. Ajgaonkar and H. Grebel, "Morphology-dependent transmission through photonic crystals", *J. Opt. Soc. Am.* (*JOSA*) *B,* 19, 285-291 (2002). J. Shah, D. Moeller, H. Grebel, O. Sternberg and J. M. Tobias, "Three-dimensional metallo-dielectric photonic crystals with cubic symmetry as stacks of two-dimensional screens", accepted by *J. Opt. Soc. Am.* (*JOSA*) *A,* 2004. The waveguide is controllable by variation of period and Δn.

[0030] Referring again to the embodiment of FIG. **2**, the receiver **40** which is preferably ultra-miniaturized, includes a photonic crystal structure which acts as a spatial dispersing element (that is, an element that spatially disperses the THz radiation into its component "colors" or frequencies), a self-focusing element to direct and focus the dispersed THz "colors" onto detector array **44**, and a filtering element. Tunable photonic crystal filters have been demonstrated in the sub-THz (70-110 GHz) frequency range. See, T. Drysdale, R. J. Blaikie, D. R. S. Cumming, 'Calculated and measured trasmittance of a tunable metallic photonic crystal filter for THz frequencies', *Appl. Phys. Lett.* 83, 5362 (2003). The operating frequency of the photonic crystal filters is realized in the appropriate THz frequency band by scaling the dimension of the photonic crystal lattice constants.

[0031] Self-focusing is achieved through the diffraction of higher-order modes from the transverse Bragg planes. See, J. M. Tobias, M. Ajgaonkar and H. Grebel, "Morphology-dependent transmission through photonic crystals", *J. Opt. Soc. Am.* (*JOSA*) *B,* 19, 285-291 (2002); H. Grebel and J. Tobias, "Study of hybrid metal-dielectric photonic crystals", QTuF1, Quantum Electronics and Laser Science 2002, San Francisco, Calif., May 2002; H. Grebel, Z. Iqbal and A. Lan, "Detection of C_{60} using surface enhanced Raman scattering from metal coated periodic structures", *Appl. Phys. Letts.,* 79, 3194-3196 (2001); J. M. Tobias and H. Grebel, "Self-imaging in photonic crystals in a sub-wavelength range", *Opt. Letts.,* 24, 1660 (1999); S. Vijayalakshmi, H. Grebel, G. Yaglioglu, R. Dorsinville and C. W. White, "Nonlinear dispersion properties of sub-wavelength photonic crystals", *Appl. Phys. Letts,* 78, 1754-1756 (2001).

[0032] The propagating modes interfere in the direction of the beam propagation along the diffracting planes. Diffraction is periodic along the direction of propagation. The distance, which separates the self-imaging planes (also known as Talbot planes), is defined as the self-imaging distance. The self-imaging distance for a periodic transverse structure obeys the relationship, $L_s \sim \Lambda^2/\lambda_n$, including inverse images. Here, Λ is the transverse pitch and λ_n is the propagating wavelength in the material, that is λ/n_{eff}, where n_{eff} is an effective index of refraction dependent on the structure as defined below. Use of this equation is usually limited to pitch values larger than the propagating wavelength. Nevertheless, if $\Lambda \sim \lambda_n$, L_s is on the order of only a few wavelengths.

[0033] In one embodiment the THz receiver **40** is fabricated as a three-dimensional photonic crystal and shaped into the form of a prism to overcome the obstacle imposed by integration of active THz detection elements within the photonic crystal structure. The THz beam, which includes many spectral components or lines, impinges on the photonic crystal prism from the left through the screen **42** which contains plural pin-holes formed therein. Wavelength dispersion dependence is such, that only a particular wavelength will be focused onto a particular detector in the array lying underneath the prism. All other wavelengths are averaged out so that the resulting signal can be removed by imaging processing techniques or the like. The prism is preferably realized using a hollow structure with a top inclining grating. A stack of two-dimensional screens is fabricated wherein resonance of each successive screen is offset such that a spatial chirp is achieved.

[0034] The receiver **40** structure may be made three-dimensional by designing a succession of metallo-dielectric screens. Each individual screen is patterned using standard silicon processing techniques on silicon wafers. A wafer bonding technique is used to attach successive screens into a composite 3-D photonic crystal structure. In the wafer bonding technique, silicon wafers are thinned by etching and bonded using heat treatment.

[0035] For an ultra-miniaturized receiver in a secure communications system, it is contemplated that an appropriate choice of channel frequencies could be near the three predominate attenuation frequencies of water vapor (e.g., 0.558 THz, 0.75 THz, and 0.98 THz) for the communications link. The overall size of the receiver for such a system would be about 10 wavelengths of 0.558 THz light or roughly 6 mm.

[0036] Secure communications using THz radiation takes advantage of the limited atmospheric propagation of submillimeter (THz) electromagnetic radiation to achieve a secure short distance (1-100 m) wireless communications link. This communications link is secure since the THz radiation (which could be encrypted) is strongly absorbed by the atmosphere (~4 dB/m) if the frequency of the link is tuned to specific frequencies (e.g. 0.557 THz). This frequency corresponds to the frequency at which strong atmospheric absorption by water vapor occurs.

[0037] Now referring to FIG. **4**, in accordance with one embodiment of the present invention a secure THz communication is established between **60** vehicles one or more of which may be manned or unmanned. A THz transmitter **20** on a vehicle **60** is modulated to transmit data through the atmosphere to a THz receiver **40** on another vehicle **60**. Conceptually, military vehicles are generally congregated in close proximity to one another before dispersing to conduct their mission as illustrated in FIG. **4**. At such a time, high speed, secure data transmission can be conducted between the vehicles **60**. Outside of the ~100 m operating range, the communications signals are indecipherable.

[0038] The maximum distance of the communications link is determined by the absorption of THz radiation by the atmosphere. FIG. **5** shows the attenuation through the atmosphere as a function of THz frequency. In the example of FIG. **5** THz attenuation through the atmosphere at a temperature of 22° C. and 8% relative humidity is shown. The strong absorption features are predominately due to water vapor absorption. Using the data of FIG. **5**, a THz communication channel tuned to 0.558 THz is attenuated approximately 1 dB/m. For short distances, the THz receiver **40** will have sufficient sensitivity to establish a communication link. However, for longer distances the attenuation is sufficiently large that the there is insufficient signal to eavesdrop on the communications channel. For example, a distance of 100 m reduces the signal by 100 dB (10 orders of magnitude). The presently disclosed THz communication system includes a THz receiver capable of high resolution (~10 GHz) at several distinct THz frequencies (e.g. 0.558, 0.75, and 0.98 THz). Each THz frequency, which can function as an independent communications channel, is preferably tuned close to a water absorption line to limit the propagation distance.

[0039] Two exemplary implementations of a THz transmitter **20** that could be employed as a part of a THz communications system, a GaAs photomixer and an integrated photomixer, are described below.

[0040] Now referring to FIG. **6** a single channel THz secure communications device in accordance with at least one embodiment of the present invention includes a GaAs photomixer employing fiber-optic pigtail cables **22** modulated (encoded with data) by varying the voltage across the GaAs device. After transmitting through the atmosphere, the THz signal is detected using a THz receiver **40** with a bandpass filter **46**. Multiple channels can be added by adding additional THz transmitters **20** and detector/filter pairs that are tuned to different THz frequencies. Fiber-pigtailed GaAs photomixers are commercially available and can be externally modulated to encode the transmitted THz radiation. Recent units available from Picometrix, LLC of Ann Arbor, Mich. have modulation bandwidths extending to 1 MHz. The photomixer configuration described above can be implemented by a monolithically integrated portable THz emitter based on difference frequency generation (DFG) in artificially birefringent III-V nanostructures. This implementation utilizes a combination of the latest achievements in the monolithic integration of InP-based high-power lasers and nonlinear birefringent active waveguides for efficient difference frequency generation in the THz spectral range. The approach is compatible with existing InP technology platform that makes it scalable for integration into THz emitting arrays. The devices are compact and consistent with man-portability in size, weight, power consumption, and geometry. The geometrical size of the InP chip can be less than 10 mm, while the size of the packaged device can be less than 30 mm. At such sizes a THz emitter "chip" is easily affixed to the outside of a vehicle and integrated into a hand-held unit.

[0041] Now referring to FIG. **7** in one embodiment a portable THz emitter **100** includes semiconductor lasers **110** and **120** and nonlinear birefringent waveguide **150**, all of which may be monolithically integrated on the same substrate **170**. Substrate **170** is preferably an InP substrate. Birefringent waveguide **150** provides phase matching for orthogonally polarized lasers **110** and **120**. Birefringent waveguide **150** may have for example Δn=0.02. Lasers **110** and **120** may have different emission energies, for example, $h\omega_1$=0.785 eV (λ_1=1.58 μm) and $h\omega_2$=0.81 eV (λ_1=1.53 μm), respectively. Fine-tuning of the waveguide birefringence is preferably controlled by the external electric field applied perpendicular to the plane of the waveguide **150**. Multiple contacts (V_1, V_2, etc.) provide additional degrees of freedom in achieving a perfect phase-matching condition. Radiation of lasers **110** and **120** may be coupled with the help of passive waveguides **112** and **122** into the active waveguide **150**.

[0042] In one embodiment the THz emitter **100** is operable for the frequency range 0.5-7 THz. Semiconductor lasers with different emission energies (wavelengths) may be employed. For example, in one embodiment laser **110** is a distributed feedback (DFB) laser with TM polarization. The polarization of the laser **110** is controlled by tensile strain in the active region. Power of laser **110** is 80 mW and the laser line width is 1 MHz. Laser **120** is a conventional distributed feedback (DFB) laser with TE polarization. Power of this laser is 100 mW and the laser line width is 1 MHz. Orthogonally polarized radiation of these lasers is coupled to the passive integrated waveguides and is mixed in the active birefringent waveguide section.

[0043] Phase matching of the laser radiation is determined by the design of the active birefringent waveguide **150**: $n(\omega_1)=n(\omega_2)=n(\omega_2-\omega_1)$. Birefringence in the waveguide **150** is produced both by the nanostructures-based active layer and by geometry. In this particular example, the difference between the laser frequencies $\omega_2-\omega_1$ falls in the THz frequency range (~6 THz). Using a typical power of the semiconductor laser of 80 -100 mW and the Manley-Rowe relation for the conversion limit: $P_{THz}=P_{laser}(\omega_2-\omega_1)/\omega_1$, the estimated upper limit for the THz emission power is 3 mW.

[0044] To make the size of the THz emitter **100** comparable to that of conventional optoelectronic devices, such as electro-absorption modulated lasers (EMLs), modulators, and amplifiers, the components of the THz emitter **100** can be monolithically integrated on the same semiconductor chip. InP-based technology of Metal-Organic Vapor Phase Epitaxy (MOVPE) in the regime of selective area growth may be employed to utilize existing technology for the lasers and passive waveguides, commonly used for telecommunications. The exemplary design in FIG. **7** can be easily modified or scaled to produce arrays of THz emitters with a fixed or variable frequency.

[0045] The phase-matching condition is controlled by the design of the birefringent waveguide **150**, which in a contemplated embodiment is comprised of InP-based nanostructures such as quantum well layers, quantum dots, vertical nanowires and the like.

[0046] In contrast to current THz emitters, which employ THz pulse generation with visible femtosecond laser operated at the pulse repetition rate in THz range, external light sources (lasers) are not required in the present designs. The present designs can employ thermoelectric cooling and do not require cryogenic temperatures like most of conventional Quantum Cascade Lasers.

[0047] The advantages of using waveguides composed of nanostructures are twofold. First, efficient nonlinear interaction is achieved due to the high value of nonlinear coefficient $\chi^{(2)}$ of III-V materials (e.g., $\chi^{(2)}$ of GaAs is equal to 240 pmV^{-1}). Second, the tremendous increase of the surface area is expected to modify the energy exchange between the three interacting electromagnetic waves controlled in general by the Manley-Rowe law. At the extended surface of the nanowires, the energy flow that goes beyond the Poynting vector should modify the limit for conversion of the optical power into THz radiation

Phase Modulation

[0048] The rate of the scanning can be increased by recognizing that the initial phase of the THz wave in the photomixing process is determined by the phase difference of the two lasers. In other words, shifting the phase of one of the infrared lasers by 2π (which corresponds to a path length change of one infrared wavelength ~0.8 μm) is equivalent to shifting the phase of the THz beam by 2π (which corresponds to a path length change of ~0.3 mm). Furthermore, rather than mechanically scanning a distance of ~1 μm, since the rate of such scanning would be limited to the 10 s of kHz range with piezo-actuators, one can directly modulate the phase of one of the lasers using an opto-electronic Lithium Niobate phase modulator. Since the speed of Lithium Niobate modulators can be as high as the gigahertz range, one can eliminate the speed limitations due to mechanical scanning in acquiring a THz waveform.

[0049] Now referring to FIG. **8**, an experimental apparatus for rapid continuous wave (CW) detection of the THz phase and amplitude is shown. THz radiation is generated at the beating frequency of two Littman external cavity diode lasers (Sacher Lion TEC520) operating near 0.78 μm. For these experiments, they are detuned by 0.6 nm which corresponds to 0.3 THz. The output of each laser is evenly split using the first pair of beam splitters. The phase modulator is inserted into one of the beams from ECDL #1. After splitting and passing one beam through the modulator, the light from the two lasers are combined with another pair of beam splitters. The combined laser light is coupled into polarization maintaining optical fibers and delivered to both the THz transmitter and receiver. The transmitter and receiver are low-Temperature-Grown GaAs bowtie-type photo-conductive dipole antennae (PDA). The total optical power on both channels is ~12 mW. A bias of 20 V DC is applied to power the THz transmitter.

[0050] THz radiation is generated by photomixing of the two laser beams in the THz transmitter. The generated THz wave can be presented as a product of electric fields,

$E_{THz}\sim E_1$ **[text missing or illegible when filed]** $E_2\sim E_1 \sin(\omega_1 t+\phi_1)E_2 \sin(\omega_2 t+\phi_2) \sim E_1E_2[\cos(\Delta\omega t+\Delta\phi_0)]$ (1)

where $\Delta\omega=\omega_1-\omega_2$, $\Delta\phi_0=\phi_1-\phi_2$, E_1 and E_2 are the amplitudes of infrared EDCL electric fields at the frequencies ω_1 and ω_2, and phases ϕ_1 and ϕ_2, respectively. In Eq. (1) it is assumed that the polarization of the two beams from ECDL #1 and #2 are parallel so that the vector dot product of the infrared E fields simply becomes a scalar multiplication.

[0051] The electro-optic phase modulator, which is inserted into the optical path of the ECDL #1 beam that will drive the THz transmitter, is oriented so that the applied voltage induces a change in refractive index along the polarization axis of the infrared laser beam. By varying the applied voltage to the phase modulator, the optical path length experienced by the propagating laser beam varies proportionally. Adding the addition phase shift $\phi_m(t)$ induced by the modulator into Eq. (1) gives

$$E_{THz}(t)\sim E_1E_2[\cos(\Delta\omega t+\Delta\phi_0+\phi_m(t))] \tag{2}$$

where the time dependant phase shift can be expressed as

$$\phi_m(t) = \frac{2\pi}{\lambda}\left[\frac{n_e^3 r_{33}}{2}\right]\frac{LV(t)}{d}. \tag{3}$$

[0052] In Eq. (3), L is the length of the $MgO:LiNbO_3$ crystal, λ is the vacuum wavelength of the ECDL laser, n_e is the refractive index of the crystal at zero voltage, r_{33} is the electrooptic coefficient, and d is the crystal thickness (and the electrode spacing). Since the phase shift is proportional to the applied voltage, a linear phase shift requires a linear increase in voltage. After passing through free space to the THz detector, the THz beam acquires a phase shift ϕ_p.

[0053] The detected THz signal is determined by mixing (multiplying) the incoming THz radiation of Eq. (2) with the two infrared ECDL signals present at the THz detector:

$E_{det} \sim E_{THz}$**[text missing or illegible when filed]**$(E_1$**[text missing or illegible when filed]**$E_2) \sim E_{THz}(t, \phi_p)E_1 \sin(\omega_1 t+\phi_3) E_2 \sin(\omega_2 t+\phi_4).$ (4)

where ϕ_3 and ϕ_4 represent the phase of the beams from ECDL #1 and #2, respectfully, at the THz receiver. Generally, $\phi_1 \neq \phi_3$ and $\phi_2 \neq \phi_4$ since the optical path length from the lasers to the transmitter is not equal to the path length from the lasers to the receiver. Simplifying Eq. (4) using Eq. (2) gives

$$E_{det}(t) \sim E_1^2 E_2^2 \cos(\phi_m(t)+\phi_p+(\phi_1-\phi_3)+(\phi_2-\phi_4)) \quad (5)$$

since the harmonic at $2\Delta\omega$ is removed by the detection electronics. Consequently, the voltage produced by the THz detector varies sinusoidally with a linear increasing applied voltage. Of course, one also has the option of generating other functional variations by electronically controlling the functional form of $\phi_m(t)$.

[0054] If a linear voltage ramp waveform with a maximum voltage swing corresponding to a 2π phase shift were applied to the modulator, then output voltage of the THz receiver would vary over a complete cycle of the cosine of Eq. (5). The output of the THz receiver can then be recorded with a digital lock-in amplifier that locks to the ramp modulation frequency. However, if the voltage swing corresponds to a phase shift that were either smaller than or larger than 2π, the output voltage from the THz receiver would not be perfectly sinusoidal. The preference for a complete 2π phase shift in the modulator is illustrated in FIGS. **9**A-**9**H. For voltages below the equivalent of 2π phase shift, (20-100V plots) the output waveforms are not complete sinusoids. For voltages that are too large (140 and 160V), a voltage swing larger than one cycle is observed. When an object is inserted between the THz TX and RX which modifies the phase shift of the propagating THz beam ϕ_p, the measured phase of the RX waveform shifts as well. To illustrate this effect, a thin business card was inserted between the THz transmitter and receiver of FIG. **8**. When the phase modulator voltage is set correctly, the phase of the THz receiver waveform shifts by 1.6 μs corresponding to a 0.32π phase shift of the THz wave as shown in FIG. **10**.

[0055] Using THz time-domain systems, the maximum measured data rate for THz wireless communication has been reported to be 1 Mbit/s. Möller, L.; Federici, J.; Sinyukov, A; Xie, C.; Lim, H.; Giles, R., "Data encoding on terahertz signals for communication and sensing", Optics Letters, 33:4, 393-395 (2008). Data is encoded on the THz pulse train by modulating the bias voltage applied to the THz transmitter. There are two limitations to this data rate: the first limitation is the electronic bandwidth (420 kHz) of the THz receivers, the second is the repetition rate (~80 MHz) of the Ti:Sapphire laser that is used to generate and detect the THz. Using the present method, increasing the bandwidth of the THz receivers beyond 80 MHz, the data rate of the fast phase modulation system exceeds that of a time-domain system.

[0056] This opto-electronic method is roughly 3 orders of magnitude faster than mechanical scanning methods. Utilizing the rapid phase modulation method enables MHz data rates for THz communication and can be applied for phase modulation in accordance with the present invention. In one embodiment phase modulation can be achieved using a Lithium Niobate phase modulator which can operate in the GHz range. The phase of the THz radiation can be directly modulated through a 2π phase shift. By varying the applied voltage to the modulator **50**, the optical path length experienced by the propagating laser beam varies proportionally. The speed of a Lithium Niobate phase modulator can be optimized in a communications system with a function generator in the hundreds of MHz range and a THz receiver having a large bandwidth response, preferably greater than 420 kHz and more preferably 80 MHz or greater.

[0057] The present inventions can be employed as wireless communication devices, and applied in any environment where deployment of same would be necessary or desirable, including but not limited to airports, military installations, mobile military units, vehicles and the like.

[0058] Applicants have attempted to disclose all embodiments and applications of the described subject matter that could be reasonably foreseen. However, there may be unforeseeable, insubstantial modifications that remain as equivalents. While the present invention has been described in conjunction with specific, exemplary embodiments thereof, it is evident that many alterations, modifications, and variations will be apparent to those skilled in the art in light of the foregoing description without departing from the spirit or scope of the present disclosure. Accordingly, the present disclosure is intended to embrace all such alterations, modifications, and variations of the above detailed description.

[0059] All references cited herein are incorporated fully by reference.

What is claimed is:

1. A THz communication device comprising a THz transmitter, a THz receiver and a modulator, wherein the THz transmitter is configured to introduce a THz signal to the modulator and the THz receiver is configured to receive the THz signal from the modulator and demodulate the signal.

2. The device of claim **1** wherein the THz transmitter is selected from a GaAs photomixer or an integrated waveguide photomixer.

3. The device of claim **1** wherein the THz transmitter is an integrated waveguide photomixer.

4. The device of claim **1** wherein the THz receiver is multichannel receiver comprising a photonic bandgap THz spectrometer.

5. The device of claim **1** wherein the receiver comprises a self-focusing element to direct and focus a dispersed THz signal, a detector array, and a filtering element

6. The device of claim **1** wherein the receiver comprises a photonic crystal prism and a pin-hole screen.

7. The device of claim **1** comprising a GaAs photomixer comprising fiber-optic pigtail cables modulated by varying the voltage across the GaAs device.

8. The device of claim **1** comprising a THz receiver comprising a bandpass filter.

9. The device of claim **1** integrated on a InP substrate.

10. An apparatus comprising a plurality of THz transmitter and receivers in accordance with claim **1**.

11. A THz communication system comprising at least one THz transmitter, at least one THz receiver and at least one modulator, wherein the at least one THz transmitter is configured to introduce a THz signal to the at least one modulator and the at least one THz receiver is configured to receive THz signals from the at least one modulator and demodulate the signals.

12. The system of claim **11** wherein the at least one THz transmitter, at least one THz receiver and at least one modulator are mounted on at least one vehicle within a range suitable for the at least one THz transmitter, at least one THz receiver and at least one modulator to transmit and receive signals.

12. The system of claim **10** wherein the at least one THz transmitter, at least one THz receiver and at least one modulator are mounted on a plurality of vehicles.

13. A portable THz emitter comprising at least two semiconductor lasers and a nonlinear birefringent waveguide monolithically integrated on the same substrate.

14. The emitter of claim **13** comprising an InP substrate.

15. The emitter of claim **13** wherein the birefringent waveguide provides phase matching for orthogonally polarized lasers.

16. The emitter of claim **13** wherein the lasers have different emission energies.

17. A method of communication using THz signals comprising:

generating a THz signal;

modulating the phase of the THz signal;

transmitting the modulated THz signal to a THz receiver; and

demodulating the THz signal at the THz receiver.

18. The method of claim **17** further including the step of generating THz radiation at the beating frequency of at least two lasers to provide individual laser beams, splitting each of the individual laser beams, mixing the split laser beams, recombining the laser beams and coupling the laser beams into fibers.

19. The method of claim **18** comprising applying a voltage to the modulator.

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