A novel MMIC on-chip power-combined frequency multiplier device and a method of fabricating the same, comprising two or more multiplying structures integrated on a single chip, wherein each of the integrated multiplying structures are electrically identical and each of the multiplying structures include one input antenna (E-probe) for receiving an input signal in the millimeter-wave, submillimeter-wave or terahertz frequency range inputted on the chip, a stripline based input matching network electrically connecting the input antennas to two or more Schottky diodes in a balanced configuration, two or more Schottky diodes that are used as nonlinear semiconductor devices to generate harmonics out of the input signal and produce the multiplied output signal, stripline based output matching networks for transmitting the output signal from the Schottky diodes to an output antenna, and an output antenna (E-probe) for transmitting the output signal off the chip into the output waveguide transmission line.
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CPC .................. H01L 2222/6627 (2013.01); H01L 2223/6677 (2013.01); H01L 2223/6683 (2013.01); H01L 2224/4899 (2013.01); H01L 2924/12032 (2013.01); H03B 2200/0032 (2013.01); H03B 2200/0076 (2013.01)

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1.6 THz 'ON-CHIP' POWER-COMBINING TRIPLER (quad-structure)
1.9 THz ‘ON-CHIP’ POWER-COMBINING (Dual-conf)
650 GHz ON-CHIP POWER-COMBINING (dual-structure—horizontal E-field feed)
Fig. 10

1000: MMIC on-chip power-combined multiplier chip lithography
1002: Micromachining Silicon Wafers (waveguide, alignment holes and screw holes formation)
1004: Gold plating silicon wafers
1006: Obtaining silicon fasteners
1008: Device assembly, Aligning, Stacking and Fastening Together
1010: Final On-chip power combined frequency multiplier
ON-CHIP POWER-COMBINING FOR HIGH-POWER SCHOTTKY DIODE BASED FREQUENCY MULTIPLIERS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. Section 119(e) of the following co-pending and commonly-assigned application:

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention
This invention relates to on-chip power combining for high-power Schottky diode based frequency multipliers.

2. Description of the Related Art.
(Note: This application references a number of different publications as indicated throughout the specification by one or more reference numbers within brackets, e.g., [x]. A list of these different publications ordered according to these reference numbers can be found below in the section entitled "References." Each of these publications is incorporated by reference herein.)

Solid-state multiplied local oscillator (LO) sources based on Schottky diode technology have been by far the preferred devices to drive the heterodyne receivers on imaging radars for concealed weapons detection and on-board planetary science and astrophysics space missions at submillimeter-waves and terahertz (THz) frequencies. The first generation of room-temperature Schottky multiplied LO sources exhibited up to 2 microwatts (µW) at 1.9 THz frequency (highest band of the HIFI instrument of the Herschel Space Observatory) by frequency multiplying from the available 100-150 milliwatt (mW) LO sources at W-band frequencies (75-100 Gigahertz, GHz) up to terahertz frequencies using a 2+3+3 (doubler, tripler, tripler) cascaded-multiplier configuration.

The recent progress in GaN-based power amplifier technology has recently demonstrated output power levels in excess of 5 Watts (W) from power amplifiers at W-band frequencies, making it now possible to conceive solid-state multiplied sources beyond 2 or 3 THz [2], as well as to develop multi-pixel heterodyne instruments for ground and space based applications in the THz range [3]. The increasing output power at W-band, together with the use of high-thermal conductivity substrates and power-combining schemes to increase the number of chips within the multipliers, have already led to world-record measured output powers up to 1.4 milliwatts (mW) at 0.9 THz, 60 microwatts (µW or uW) at 1.9 THz [1], and 15 µW at 2.54 THz at the Jet Propulsion Laboratory (JPL).

Using the novel GaN amplifier chains, power levels up to 10 mW at 600 GHz and >0.1 mW at 1.9 THz are envisioned using all-solid-state frequency multiplied sources.

Since the maximum power handled by a single chip is generally limited by the number of diodes in the chip, a number of multiplier chips need to be power-combined in order to make it possible to handle high amounts of power at the input and subsequently produce superior power levels at the output. However, the use of traditional power-combining topologies, already demonstrated below 1 THz, presents inconvenience beyond 1 THz. On the other hand, the use of Y-junction to divide/combine the input/output power at these frequency bands unnecessarily increases the electrical path of the signal at a range of frequencies where waveguide losses are considerably high. On the other hand, guaranteeing a perfect alignment of the very small chips during assembly, in order to preserve the balanced nature of the multiplier, is practically impossible, with a subsequent impact on the multiplier performance. Hence, novel power-combining schemes are very necessary in order to increase the power-handling capabilities of high-frequency multipliers, while preserving the multiplier circuit performance. The present invention satisfies this need.

SUMMARY OF THE INVENTION

One or more embodiments of the invention disclose a Monolithic Microwave Integrated Circuit (MMIC) multiplier device, comprising: two or more multiplying structures integrated on a single chip, wherein each of the integrated multiplying structures are electrically identical and each of the multiplying structures include one input antenna (E-probe) for receiving an input signal inputted on the chip, a stripline based input matching network electrically connecting the input antennas to one or more Schottky diodes, two or more Schottky diodes that are used as nonlinear semiconductor devices to generate harmonics out of the input signal and produce the multiplied output signal, stripline based output matching networks for transmitting the output signal from the Schottky diodes to an output antenna, and an output antenna (E-probe) for transmitting the output signal off the chip into the output waveguide transmission line.

The factor of improvement in terms of power handling capabilities and output power with regards to traditional frequency multiplier devices is directly proportional to the number of multiplying structures included on the on-chip power-combined MMIC device.

The frequency of the input signal can be W-band or higher, i.e. within the terahertz range (100 GHz-3 THz). The output frequency can be twice or three times the input signal depending on the multiplier type. The MMIC multiplier device features one antenna (E-probe) per multiplying structure. The 2 or more antennas of the whole chip are symmetrically placed within the plane normal to the propagation of the incident electrical field (TE10 mode of the input waveguide). The 2 or more antennas thereby split evenly the incident power among the 2 or more multiplying structures included on the same MMIC chip.

Two or more Schottky diodes are included in each of the multiplying structures symmetrically placed within the chip plane along the direction of the E-field vector so that the power is delivered in-phase to the diodes. The diodes are connected to the input antennas or E-probes through metal stripline transmission lines that provide the diodes with optimum power matching. The position of the diodes within each of the multiplying structures is optimized so that each of the diodes receives an equal part of the input power. The number
of diodes included in the MMIC chip is defined by the specific frequency of operation, the desired bandwidth and the nominal input power of operation, but can be 2 or more per multiplying structures, i.e. four or more diodes total in the whole chip assuming a dual-multiplier configuration and 8 or more diodes total in the whole chip if the quad configuration. The nonlinear nature of the capacitance vs. voltage and/or the resistance vs. voltage characteristics of the diodes generate harmonics of the input signal. The position of the diodes and circuit matching elements are designed to enhance the performance at the second harmonic for a frequency doubler or the third harmonic for a frequency tripler.

The Schottky diodes are electrically connected to output antennas or E-probes by means of stripline based matching elements that guarantee that most of the power generated by the diodes at two times the frequency of the input signal (2x100 GHz or more for a doubler, or 3x100 GHz or more for a tripler) is transferred off the integrated circuit to the output waveguide.

Accordingly to the definitions above, the integrated circuit (MMIC device) has a pattern that is symmetric about at least two axes passing through a central point of the integrated circuit within the plane normal to the propagation of the incident submillimeter-wave or terahertz electrical field.

The MMIC multiplier devices including the 2 or more multiplying structures can be lithographically patterned (e.g., using photolithography, Monolithic Microwave Integrated Circuit (MMIC) lithography, metal deposition, etc.) on a Gallium Arsenide (typical), Quartz, Silicon carbide, Iadium Phosphide diamond, Gallium nitride or any other material wafer. The device further comprises additional stripline metallizations that provide the chip with dec bias connections for each of the two or more multiplying structures, which are used to optimize the performance of the chip for high input power levels, as well as appropriate ground connections to a waveguide block where the chips are assembled. Therefore, the device further comprises one input submillimeter-wave or terahertz waveguide structure that couples the submillimeter-wave or terahertz signal to the input antennas included in the MMIC. The input waveguide structure includes additional input matching elements to guarantee a wide frequency bandwidth of operation for the on-chip power-combined frequency multiplier. Using the same concept, two output waveguides receive the output frequency multiplied signal from the output antennas within the chip and transmit the signal of the multiplier block. Each of the output waveguides receives one half of the total output power produced in the multiplier chip. The chip is placed in a small waveguide channel between the input and output waveguides.

The waveguide housing for the chip can be done using either very thin metal plates (typically 3 millimeter (mm)-thick or less gold plated brass plates) or very thin metal plated (typically gold plated) silicon wafers vertically stacked along the axis perpendicular to the on-chip power-combined device plane. The complete multiplier housing block can comprise a plurality of aligned, stacked, and fastened/attatched silicon or metal plates featuring the input and output waveguide matching structures, the waveguide channel where the chip is assembled, the bias circuitry, via holes for alignment pins, screw holes, and input and output waveguide flanges to provide the multiplier block with appropriate connectivity to other circuits.

Silicon-based housing blocks are typically employed for input frequencies of 500 GHz or higher since the thickness of each of the plates that forms the stacked block can be less than 2 mm-thick. This thickness is defined by the length of the input/output waveguide matching sections, which depends on the operation frequency. Metal plates thinner than 3 mm are very hard to machine using conventional CNC machining techniques. The total thickness of the multiplier device including the input waveguide, output waveguides and the integrated circuit, along a longitudinal axis of the input waveguide and output waveguides, can be less than five micrometers.

The total dimension of the multiplier device including the input waveguide, output waveguides and the integrated circuit, along a longitudinal axis of the input waveguide and output waveguides, can be less than 1 millimeterx1 millimeter.

The invention can be applied to frequency multipliers at any frequency of operation. For example, frequency triplers have been designed and fabricated at the Jet Propulsion Laboratory with the following characteristics:

(a) 550 GHz on-chip power combined frequency tripler on a quad-configuration comprising four multiplying structures with 2 diodes each, center frequency of operation (output): 550 GHz, frequency bandwidth of at least 15%, input power 100 mW, output conversion efficiency: 5-7%, output power 5-7 mW;
(b) 650 GHz on-chip power combined frequency tripler on a quad-configuration comprising four multiplying structures with 2 diodes each, center frequency of operation (output): 650 GHz, frequency bandwidth of at least 15%, input power 100 mW, output conversion efficiency: 5-7%, output power 5-7 mW;
(c) 650 GHz on-chip power combined frequency tripler on a dual-configuration comprising two multiplying structures with 2 diodes each, center frequency of operation (output): 650 GHz, frequency bandwidth of at least 15%, input power 50 mW, output conversion efficiency: 5-7%, output power 2.5-3.5 mW;
(d) 1600 GHz on-chip power combined frequency tripler on a quad-configuration comprising four multiplying structures with 2 diodes each, center frequency of operation (output): 1600 GHz, frequency bandwidth of at least 15%, input power 32 mW, output conversion efficiency: 2-3%, output power 0.65-1 mW;
(e) 1900 GHz on-chip power combined frequency tripler on a quad-configuration comprising four multiplying structures with 2 diodes each, center frequency of operation (output): 1900 GHz, frequency bandwidth of at least 15%, input power 4 mW, output power 20-22 uW;
(f) 1900 GHz on-chip power combined frequency tripler on a dual-configuration: Two multiplying structures with 2 diodes each, center frequency of operation (output): 1900 GHz, frequency bandwidth of at least 15%, input power 2 mW, output power 10-12 µW.

The method can further comprise obtaining/fabricating one or more machined silicon fasteners (e.g., silicon pins), wherein the silicon wafers are fastened/attatched together with the integrated circuit between the input waveguide and the output waveguides, by insertion of the machined silicon fasteners into the fastening holes in each of the silicon wafers.

In one embodiment of the present invention, a novel concept for on-chip power-combined high-power frequency multipliers featuring two or more multiplying structures integrated on a single-chip with the input and output waveguides perpendicular to the waveguide channels is described. The input power is equally divided in-phase by two or more E-probes located at the input waveguide. The produced output power is recombined at the output using the same concept. Each of the two individual waveguide outputs provide one half of the total power generated from the input signal. The
improvement factor in input/output power is directly proportional to the number of multiplying structures included in the chip.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1(a) is an 'on-chip' power combining scheme for frequency multipliers, according to one or more embodiments of the invention.

FIG. 1(b) illustrates an on chip power combining scheme and input and output waveguides for generating 1.6 THz using four on-chip multiplying structures and eight Schottky diodes total, according to one or more embodiments of the invention;

FIG. 1(c) illustrates an on chip power combining scheme and input and output waveguides for generating 650 GHz using two on-chip multiplying structures and four Schottky diodes total, according to one or more embodiments of the invention, wherein the E-field excitation to the chip is through and input waveguide along the same plane as the one where the chip is located.

FIG. 2 is a close-up view of the on-chip power-combined MMIC device, according to one or more embodiments of the invention, wherein four dc beamleads provide independent bias to each diode branch, if fine tuning of the tripler performance is not required, only a single bias line would be necessary; and four input E-probes or antennas divide the input power evenly among the four multiplying structures.

FIG. 3(a) is a predicted performance of the on-chip power combined 1.6 THz frequency tripler for an input power of 32 mW, according to one or more embodiments of the invention;

FIG. 3(b) is a predicted performance of the on-chip power combined 1.9 THz frequency tripler (single configuration, dual configuration and quad configuration) for an input power of 1, 2 and 4 mW respectively, according to one or more embodiments of the invention;

FIG. 3(c) is a predicted performance of the on-chip power combined 550 GHz, 650 GHz and 1900 GHz frequency triplers, according to one or more embodiments of the invention;

FIG. 4(a) illustrates a close up view of an on chip power combining scheme for generating 1.6 THz using eight Schottky diodes (or four balanced pairs of Schottky diodes), according to one or more embodiments of the invention;

FIG. 4(b) is a Scanning Electron Microscope (SEM) image of the scheme illustrated in FIG. 4(a), according to one or more embodiments of the invention;

FIG. 5(a) illustrates a close up view of an on chip power combining scheme for generating 1.9 THz using four Schottky diodes (or two balanced pairs of Schottky diodes), according to one or more embodiments of the invention;

FIG. 5(b) illustrates a close up view of an on chip power combining scheme for generating 650 GHz using four Schottky diodes (or two balanced pairs of Schottky diodes), according to one or more embodiments of the invention;

FIG. 5(c) is an SEM image of the scheme illustrated in FIG. 5(a), according to one or more embodiments of the invention;

FIG. 6 is a quadruple power-combined 1.6 THz Schottky diode tripler using traditional power-combined techniques based on Y-junctions;

FIG. 7 is a conversion efficiency of a single-chip 1.6 THz frequency tripler a quad-chip power combined 1.6 THz frequency tripler using the traditional power-combining techniques, illustrated in FIG. 6, and an on-chip power-combined 1.6 THz Schottky diode tripler (FIG. 1(b)) according to one or more embodiments of the invention;

FIG. 8 is a final scheme of an on-chip power combined 1.6 THz Schottky tripler, including the input matching and output Y-junction to combine the two inherent outputs together (top), according to one or more embodiments of the invention, wherein the block design for Silicon micromachining features eight 0.245 mm-thick Silicon wafers (bottom left), a detailed view of the Silicon wafer where the chip(s) are located is also illustrated (bottom right), and the full block dimensions are 20×20×1.96 mm.

FIG. 9(a)-(h) is a flow chart and schematics illustrating a method of fabricating a Schottky diode based frequency multiplier device including an integrated circuit, according to one or more embodiments of the present invention.

FIG. 10 illustrates a method of fabricating a frequency multiplier device on a silicon micromachined waveguide block, according to one or more embodiments of the invention.

DETAILED DESCRIPTION OF THE INVENTION

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

In spite of the fact that some specific circuit designs at certain operation frequencies within the submillimeter-wave and terahertz ranges are used as reference to describe the invention, the described topology is applicable to any frequency range, input power levels, number of diodes and bias condition. All these different conditions shall be covered with the present patent application.

Technical Description

One or more embodiments of the present invention disclose a novel power-combined Schottky frequency multiplier topology intended to increase by a number of 2 or more the power handling capabilities of traditional single-chip frequency multipliers. The design of Schottky based multipliers at these frequency ranges is mainly constrained by the shrinkage of the waveguide dimensions with frequency and the minimum diode mesa sizes, which limits to two the maximum number of diodes per chip. Hence, multiple chip power-combined schemes become necessary to increase the power-handling capabilities of high frequency multipliers. However, the use of traditional power-combining topologies already demonstrated at frequencies below 1 THz [1, 4] presents several challenges for frequencies beyond 1 THz. On the one hand, the use of several Y-junctions or hybrid couplers to divide/combine the input/output power at these frequency bands increases unnecessarily the electrical path of the signal at a range of frequencies where the waveguide losses are considerably high. On the other hand, guaranteeing a perfect alignment of the very small chips during assembly in order to preserve the balanced nature of the multiplier is practically impossible, with the subsequent impact on the multiplier performance.

FIG. 1(a-d) illustrates the novel 'on-chip' power combining scheme for frequency multipliers which overcomes these difficulties by performing the power-combining directly 'on-
propagation of the input waveguide) with E-field line direc-

total output power each are available, which can be recom-

to well define the small dimensions of the terahertz transmission waveguides.

Contrarily to traditional frequency triplers, in this design the longitudinal axis of the input and output waveguides 104 and output waveguides 108 are perpendicular to the E-plane of both the input waveguide 104 and output waveguide 108. This is important to remark that for low frequencies of operation within the submillimeter-range, very thin metal plates instead of silicon may be used to obtain the 3D stack. The advantage of using silicon is that silicon layers thinner than 1 mm can be used (3 mm is the minimum for metal plates using CNC milling). Moreover, with silicon micro-machining, the waveguide structures are formed using (deep reactive ion etching) DRIE techniques, much more precise (better than 1 µm) than CNC milling (<5-10 µm accuracy).

The concept shown in FIG. 1(a) has been applied to the design of a high-power 1.6 THz tripler able to handle between 30-40 mW of input power with and expected efficiency of ~2-3% over a ±17% bandwidth, which is similar to that simulated for a equivalent single-chip tripler with a single balanced pair of Schottky diodes driven with four times less input power. The incident electrical field (TE 10 mode of the waveguide) is electrically connecting the input antennas to two or more Schottky diodes 105, two or more Schottky diodes that are used as nonlinear semiconductor devices to generate harmonics out of the input signal and produce the multiplied output signal, stripline based output matching networks for transmitting the output signal from the Schottky diodes to an output antenna 107, and an output antenna (E-probe) for transmitting the output signal off the chip into the output waveguide transmission line 108.

The same concept is applied to recombine the power at the output. Two output E-probes or antenna feed each of the two output waveguides 218. This prevents the need of using waveguide-based power dividing structures that would add undesired excess losses to the circuit. In addition, the balance and symmetry of the circuit with this new approach, which is crucial to obtain a good performance in any power-combined frequency multiplier at terahertz frequencies [4, 7], lies on the superior accuracy of the lithographic fabrication of the MMIC chip and Silicon micro-machined blocks (<1 micrometer (µm)) rather than on the tolerances involved with manual assembly of a number of independent chips (see FIG. 6) and traditional metal milling (5-10 µm). This could represent a big step for future multipliers operating beyond 1 THz where dimensions of critical elements of the device can be as low as 10-20 µm between 1-2 THz, and 5-10 µm beyond 2 THz.
Note that this topology inherently provides two independent outputs $204a-b$ that can be either combined together using a Y-junction, as shown in FIG. 1(a), or used to feed two independent frequency mixers in order to enable direct multipixel operation.

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**On-Chip Power Combined Multiplier Design**

The complete power-combined multipliers are designed using the software and iterative methodology presented in detailed in [1] for a traditional single-chip Schottky diode based frequency multiplier. This iterative process involves the use of Ansoft HFSS or similar for the electromagnetic simulation of the multiplier architecture and Agilent ADS or similar for nonlinear simulation of the Schottky diode device and the harmonic balance optimization of the matching circuitry.

Once the input power has been split at the input probe $206a-d$ level, the topology in FIG. 2 can be seen as four identical frequency triplers $208$ located at four independent small waveguide channels $210$ between the input waveguide $202$ and output waveguides $204a-b$. Each of these multiplying structures $208$ features two or more Schottky planar varactor diodes $212a-b$ and has several stripline sections $214$ of low and high impedance used to match the diodes at the input and output frequencies and to prevent the third harmonic from leaking into the input waveguide $202$. In order to balance each multiplying structure $216$, the dimensions of both the channel $210$ and the circuit $216$ are chosen to cut off the TE-mode at the second (idler) frequency. The dimensions of the output waveguide $204a-b$ ensure that the first and second harmonics are cut off at the output, and the balanced configuration of the diodes $212a-b$ ensures that the power levels from all the even harmonics of the input signal are strongly suppressed. The design is completed with a series of waveguide sections to provide broadband input matching to the diodes.

The predicted performance of the on-chip power combined 1.6 THz frequency tripler of FIG. 1(a), for a 32 mW input power, is presented in FIG. 3(a). A conversion efficiency of 2-3% is expected over a -20% bandwidth. The output power of a design at 1.9 THz is presented in FIG. 3(b) for three different configurations: single $306$, dual $304$ and quad-structure $302$, wherein the claimed increase in output power proportional to the number of multiplying structures within the chip is shown. In FIG. 3(c), the performance of quad on-chip power combined triplers at different frequencies are shown to demonstrate that the concept can be used at any operation frequency.

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FIG. 4(a) shows a close-view of the 'on-chip' power-combined frequency multiplier chip $400$ (featuring four multiplying structures $406$) already illustrated in FIG. 1(a) including four input antennas or E-probes $402a-d$ that evenly split by a factor of 4 the input power inputted through the TE10 mode of an input waveguide transmission line. The input electric field can be at any frequency bandwidth within the millimeter, submillimeter-wave and terahertz range. The antennas are electrically connected to the diodes by means of an input matching network $404$ formed by stripline transmission lines (of high and low impedance) that guarantee that almost all the inputted power is transmitted to the diodes as well as guarantee that the third harmonic is not transferred back to the input. The antennas and input/output matching networks can be formed including one or more materials (generally a semiconductor substrate to support the striplines, and metals for the striplines).

Each of the Schottky diodes $408$ receives one of the portions of the input power from the transmission lines $404$. Each of the Schottky diodes $408$ then frequency multiplies the input frequency to generate the frequency multiplied output signal. The balance configuration of the diodes and the waveguide channel where the diodes are located guarantee that only the desired multiplication product of the input signal is transferred to the output. The Schottky diodes $408$ are disposed in balanced pairs that suppress power from all even harmonics of the W-band electric field (for the case of a frequency tripler).

An output matching stripline $410$ electrically connects the Schottky diodes $408$ with the output antennas or E-probes $414$ that transmit the frequency multiplied signal out of the chip into the output waveguide.

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Also shown are DC bias lines $412$ for the Schottky diodes $408$.

FIG. 4(b) is an SEM image of the scheme illustrated in FIG. 4(a).

FIG. 5(a) illustrates a close up view of an on chip power combining scheme for generating 1.9 THz using two multi-structure instead of four; according to one or more embodiments of the invention. In FIG. 5, orthogonal x, y and z coordinate axes are also shown.

FIG. 5(b) illustrates a variation of the 'on-chip' power-combined multiplier chip with the two multiplying structures $406$ mirrored along a single axis. With this configuration, the input antennas can be excited with both an input waveguide perpendicular to the chip plane, or an input waveguide with its longitudinal axis in the same plane as the chip plane. This make it compatible with traditional split waveguide multipliers blocks fabricated using standard CNC milling.

FIG. 5(c) is an SEM image of the scheme illustrated in FIG. 5(a).

**Comparison Between On-Chip Power Combining and Traditional Quad-Chip Power Combining**

In order to evaluate the advantages of the proposed multiplier scheme over other power-combining techniques, an equivalent quad-chip frequency tripler has been designed following the same specifications and identical number of diodes an anode sizes, as shown in FIG. 6.

FIG. 6 shows that in this case, two levels of Y-junctions $600a-b$ at the input waveguide $602$, and two levels of Y-junctions $604a-b$ at the output waveguide $606$ have been employed to divide/combine the input/output signals. The scheme is similar to that proposed in [7]. The main constraints for this quad-chip $608$ design is the high waveguide losses due to a large electrical length necessary to split/combine the power, and the necessity to use at least two dc bias feed throughs $610$ so that the bias connector can be placed in the top of the metal block. This sets a minimum distance between the multiplier chips $608$ and leads to an undesired increase in the electrical path $612$ of the output signal (17 wavelengths $\lambda$ of the output signal), as can be seen in FIG. 6.

However, for the on-chip power-combined topology of one or more embodiments of the present invention, the complexity of the bias circuitry is greatly reduced since it can be placed on a plane perpendicular to the input and output waveguides. The electrical path of the output signal $118$ is then around $3\lambda$ (see FIG. 1), which implies a reduction of more than a factor of 5 in the output waveguide losses.

The comparison between the two architectures is plotted in FIG. 7, together with the simulated performance of a single-chip 1.6 THz tripler designed for 8 mW (one fourth of the input power of the power-combined multiplier). This single chip corresponds to one of the branches or chips $608$ shown in FIG. 6. FIG. 7 clearly shows the degradation in the conversion efficiency of the quad-chip tripler based on traditional power-combined schemes $700$, mainly due to the waveguide losses connected with the necessity of using a number of Y-junctions $600a-b$, $604a-604d$ to power-combine the input and output.
bias lines 816, and input waveguide block dimensions that would be necessary for a traditional performed using Silicon (Si) alignment pins 824 of diameters required wafers depends on the necessary bandwidth of the radation due to circuit imbalances are avoided. While combined tripler (black solid line 702) exhibits an efficiency very terning of the Schottky diode mesa

located, and the input 804a-e and output

thin Silicon wafers (µm)-thick Silicon wafers (FIG. 1a). FIG. 8 illustrates this concept similar to traditional

metal plates, around 3 mm-thick for low frequencies within the waveguide circuits (which might be replaced for very thin wafer thickness down to the thickness required for the submillimeter-wave circuit, usually 2-5 μm. Metal air-bridges 906a for the dc bias line and the ground (gnd) connections are deposited at this point as well, as shown in FIG. 9(e).

Blocks 908 and 910 represents the removal of the unnecessary parts of the GaAs substrate so that the complete chip can be released. During this step, the chip can be attached to a carrier wafer (e.g., sapphire 908a) using wax 908b and the substrate can be removed using an AlGaAs etch stop layer 909g, as shown in FIG. 9(f), and the chip/device can then be removed from the carrier wafer as shown in FIG. 9(g). FIG. 9(g) also illustrates formation of an RF probe 910a.

Block 912 and FIG. 9(h) represent the installation and fastening of the device within the mechanical block (inside the waveguide channel machined specifically for this goal (see 206 in FIG. 2)).

Steps can be added, or omitted, or performed in a different order, as desired.

Accordingly, FIG. 9 illustrates a method for fabricating an integrated circuit, comprising: Schottky diode ohmic and mesa definition (Block 900), forming of the interconnect metal by means of metal airbridges (Block 902) (input/output matching striplines sections, direct current (DC) bias lines using beamleads can be disposed in Block 906 to bias each of the Schottky diodes 408. The integrated circuit dc bias lines can be connected to external bias lines that can be formed directly on the silicon wafer that includes the waveguide channel where the chip is located or otherwise using wire-bonded capacitors placed on a small waveguide channel.

The integrated circuit 400 of one or more embodiments of the present invention (see FIG. 1(a-c)), FIG. 2, FIG. 4(a), FIG. 5) can comprise repeated instances of the circuitry on the chip 608 of FIG. 6. The rectangle 500 illustrated in FIG. 5(a) encloses the circuitry found on the chip 608. Accordingly, the integrated circuit 400 can contain, on a single chip, more than one instance of the circuitry enclosed by the rectangle 500. For example, FIG. 4(a) illustrates an embodiment of a chip 400 with four instances/repeats of the circuitry in the rect-
angle 500, and FIGS. 5 and 5(b) illustrates an embodiment of a chip with two instances/repeats of the circuitry in the rectangle 500.

The method of FIG. 9 can be used to fabricate a novel MMIC on-chip power-combined frequency multiplier device, comprising two or more multiplying structures 406 integrated on a single chip 400, wherein each of the integrated multiplying structures are electrically identical and each of the multiplying structures 406 include one input antenna (or E-probe 402a) for receiving an input signal in the millimeter-wave, submillimeter-wave or terahertz frequency range inputted on the chip, a stripline based input matching network 404 electrically connecting the input antennas to two or more Schottky diodes 408 in a balanced configuration, two or more Schottky diodes 408 that are used as nonlinear semiconductor devices to generate harmonics out of the input signal and produce an amplified output signal, stripline based output matching networks 410 for transmitting the output signal from the Schottky diodes 408 to an output antenna 414, and an output antenna (E-probe 414) for transmitting the output signal off the chip 400 into the output waveguide transmission line 800g/h.

A novelty of one or more embodiments of the invention is that the power-combining is performed directly on chip 400 contrary to the traditional power-combining schemes. The two or more input antennas or E-probes 402a divide the input signal equally among the multiplying structures 406 within the chip 400 and re-combine it at the output 204a-b using the same concept. An improvement in power-handling capabilities and output power of a factor equal to the number of multiplying structures 406 included in the chip 400 can be achieved.

The circuit can have a pattern that is symmetric about at least two axes passing through a central point of the circuit. FIG. 9 also shows the integrated circuit comprising the millimeter-wave, submillimeter-wave or terahertz stripline antennas 402a, 414, transmission lines 404, 410, and semiconductor device (for example, Schottky diodes 408 are typical for frequency multipliers) can be lithographically patterned on a semi-insulating semiconductor substrate 900f (typically 2-50 um-thick GaAs) and deposited on a plated silicon-wafer based housing or a metal-plated block, as shown in FIG. 8.

The integrated circuit fabricated using the method of FIG. 9 can include at least one pair of balanced Schottky diodes 408 per multiplying structure 406, i.e. at least two pairs for a dual on-chip multiplier configuration and at least four pairs for a quad on-chip multiplier configuration. The diodes 408 are typically nonlinear semiconductor devices that generate harmonic of the input signal so that the input signal is multiplied up in frequency.

FIG. 10 illustrates a method of fabricating a frequency multiplier device, according to one or more embodiments of the invention (referring also to FIG. 1, FIG. 2, FIG. 4(a) and FIG. 8).

The method can comprise the following steps.

Block 1002 represents micro-machining a plurality of output silicon or semiconductor wafers 800g-h, wherein the output silicon wafers aligned with the multiplier chip, stacked, and fastened together form the frequency multiplier circuit. The dimensions of the output waveguides can ensure that first and second harmonics of the input W-band frequencies are cut off at an output from the output waveguides. Micro-machining can include machining dimensions down to 10 micrometers or less, for example. One or more dimensions of each input silicon wafer 800a-e can be machined wherein each input silicon wafer 800a-e is dimensioned to be impedance matched to the on-chip power-combined frequency multiplier integrated chip 400 at the frequency bandwidth of operation. One or more dimensions of each output silicon wafer 800g-h can be machined wherein each output silicon wafer is impedance matched to the on-chip power-combined frequency multiplier integrated chip 400 at the frequency bandwidth of operation.

Blocks 1000 and 1002 can further include micromachining/formation of waveguide alignment holes and screw holes. Block 1004 represents the gold metal plating or gold metal sputtering of the silicon wafers.

Block 1006 represents obtaining/fabricating one or more machined silicon fasteners 812, wherein the silicon wafers 800a-h are fastened together by insertion of the micromachined silicon fasteners 812 into the fastening holes 824 in each of the input silicon wafers 800a-f.

Block 1008 represents aligning, stacking, and fastening together the micro-machined input silicon wafers 800a-h, wherein the integrated circuit 400 is between the input silicon wafers 800a-e and the output silicon wafers 800g-h, the input waveguide 202 inputs a millimeter-wave, submillimeter-wave or terahertz electric field on the Schottky diode based frequency multiplier chip 400.

Block 1010 represents the circuit once completed using the above steps (e.g., as illustrated in FIG. 8). Moreover, embodiments of the present invention can include the input/output circuit components 400 designed for frequencies other than millimeter-, submillimeter waves and terahertz signals, frequency multiplying semiconductor devices 208 other than Schottky diodes 408. In addition, the present invention is not limited to particular electric field. Any input electromagnetic field/radiation can be used, for example.

Steps can be added, or omitted, or performed in a different order, as desired.

Embodiments of the present invention enable the fabrication of waveguides consisting essentially of silicon or semiconductor (e.g., using silicon where metal was conventionally used). The steps of Blocks 1000-1002 can comprise micro-machining a plurality of silicon wafers 800a-h, or metal thin plates, including the input 804a-e and output 806 waveguide matching networks as well as the waveguide channel 802 where the chip is placed. The silicon wafers 800a-h (or metal thin plates) can be aligned, stacked, and fastened together using alignment pins 824, screw holes or any other alignment technique, as illustrated in Block 1008.

The method can further include, as represented in Blocks 1000-1002, machining one or more fastening holes 824 in each of the silicon 800a-h or metal wafers; machining mounting holes for external connectors; and obtaining, as represented in Block 1006, one or more machined silicon fasteners 824 (if silicon wafers are used), wherein the silicon wafers are fastened together with the integrated circuit 400 between the input waveguide 202 and the output waveguide 204, by insertion of the micromachined silicon fasteners 824 into the fastening holes in each of the wafers.
The method can also further comprise selecting the adequate number of wafers 800a-h, and adequate thickness, length L and width W of the silicon 800a-h (or metal) wafers so that all the waveguide structures, alignment elements, fastening elements, connectors can fit in the minimum possible volume for compactness.

FIG. 9 and FIG. 10 can also illustrate forming DC bias lines on the silicon wafer or metal plates to bias the Schottky diodes; aligning and assembling the chip within the waveguide housing, as shown in Block 1008 (silicon wafer or metal thin plates), wherein the input waveguide 104, 202, 804a-e inputs the electric field on the input antennas 402a within the chip 400, the output waveguides 204/806 receive the output electric field transmitted from all the output antennas 414 or E-probes, and the integrated circuit generally positioned in a plane perpendicular to a longitudinal axis or E-plane of the input 104 and output 108 waveguides.

The method of FIG. 10 can fabricate the device comprising the input waveguide matching network, i.e. waveguide matching sections 806 of different length and height to optimally couple the output electric field (multiplied by the Schottky diodes 408) in the millimeter-wave, submillimeter-wave or terahertz range into the antennas or E-probes 402a within the chip 400 while guaranteeing a broadband frequency operation.

The method of FIG. 10 can fabricate the device comprising an output waveguide matching network 806, i.e. waveguide matching sections 806 of different length and height to optimally couple the output electric field (multiplied by the Schottky diodes 408) in the millimeter-wave, submillimeter-wave or terahertz range out of the while guaranteeing a broadband frequency operation.

The waveguide structures can be formed either on one or more aligned Silicon wafers 800a-e, 800g-h using deep reactive ion etching techniques (DRIE) and subsequent gold plating Block 1004, FIG. 8, or, for low frequencies of operation, on aligned thin metal plates using traditional CNC milling techniques. The different wafers 800a-h are arranged vertically, along the axis perpendicular to the chip 400 plane to allow for a 3D integration capability. The input 104 and output 108 waveguide are generally placed perpendicular to the chip 100, 400 so that the input 402a and output 414 probes are in-phase with the fundamental mode of propagation in the input 104 and output 108 waveguide. Only in one configuration, the dual on-chip power-combined frequency multiplier topology with the two multiplying structures mirrored along the same axis, the E-plane of the input and output waveguides can be the same as the chip plane.

A total thickness of the device including the metal lines and the support substrate can be 3 um-50 um, and the total dimension of the device can be less than 3 mm×2 mm.

The operation frequency can be at the millimeter-wave, submillimeter-wave or terahertz range depending on the size and structure of the Schottky diodes 408 employed (see FIG. 9(e), the specific dimensions of the input 404 and output 410 matching structures on-chip 400 and the dimensions of the input 804a-e/202 and output 806/204a-b waveguides. The typical operation bandwidth is around 17%, but can be lower or higher depending of the specific needs. Two independent waveguide outputs 204a-b are inherently available so that the invention can feed two higher frequency multiplier stages or two frequency mixers or detectors without the need of additional waveguide based power dividers. The two outputs 204a-b can be combined using a simple waveguide Y-junction 806/1145 if one single output is desired.

The method can further comprise a previous design phase, comprising, for the desired input power, efficiency and operation frequency and bandwidth within the millimeter-wave, submillimeter-wave or terahertz range: (a) selecting a number of Schottky diodes 408 and its size and layer structure (see FIG. 9(a)); (b) designing the stripline matching elements 404, 410 within the chip as well as the input 402a and output E-probes 414, and (c) designing the input 804a-e/202 and output 806/204a-b waveguide matching network.

Advantages and Improvements

The method of Schottky based multipliers at these frequency ranges is mainly constrained by the shrinkage of the waveguide dimensions with frequency and the minimum diode mesa sizes, which limits to two the maximum number of diodes per chip. Hence, multiple chip power-combined schemes become necessary to increase the power-handling capabilities of high-frequency multipliers. However, using separate chips and traditional power-combining schemes to enhance the power capabilities is extremely complicated at very high frequencies due to the impossibility of guaranteeing a perfect alignment and symmetry of the chips. Note that chips can have dimensions below 300 µm×50 µm at signal/electric field frequencies over 1.5 THz.

One or more embodiments of the power-combining scheme of the present invention takes advantage of the possibilities offered by the Silicon micromachining, not only from a geometrical point of view (i.e. the possibility of placing the transmission waveguides following different longitudinal axis), but also from the point of view of accuracy. Since the power-combining is performed ‘on chip’, the electrical path of the signal can be reduced almost by a factor of 10 with regard to traditional power-combining schemes based on regular micro-machining and Y-junctions and/or hybrid couplers, along with subsequent reduction in the waveguide losses. In addition, since the four multiplying structures 208 are on a single chip, the circuit symmetry and alignments are no longer determined by the tolerances involved in the regular metal block micro-machining and the subsequent manual assembly of the chips, but by the superior accuracy provided by Silicon-micromachining and the MMC micro-fabrication process at JPL’s Micro Devices Laboratory (MDL).

The use of Silicon micromachining instead of metal milling also makes it possible to considerably reduce the mass and volume of the multipliers.

Embodiments of the present invention can enable high-power all-solid state terahertz local oscillator sources for multi-pixel spectroscopy at 1.9 THz and 2.7 THz, for example. Embodiments of the present invention can extend the use of Schottky technology up to at least 4.7 THz, for example.

A novelty of the invention is that the power-combining is performed directly on chip contrarily to the traditional power-combining schemes. The two or more input antennas or E-probes divide the input signal equally among the multiplying structures within the chip and re-combine it at the output using the same concept. An improvement in power-handling capabilities and output power of a factor equal to the number of multiplying structures included in the chip is achieved.

References

The following references are incorporated by reference herein.

two or more of the output antennas or output E-probes combine the output signals at the output waveguide; and an improvement in power-handling capabilities and output power of a factor equal to a number of the multiplying structures included in the chip is achieved.

2. The device of claim 1, wherein the integrated circuit comprises:

the input antennas and output antennas including millimeter-wave, submillimeter-wave, or terahertz stripline antennas,
the stripline based input and output matching networks including transmission lines, the Schottky diodes that are semiconductor devices, and the millimeter-wave, submillimeter-wave, or terahertz stripline antennas, the transmission lines, and the semiconductor devices lithographically patterned on a semi-insulating semiconductor substrate and deposited on a plated silicon-wafer based housing or a metal-plated block.

3. The device of claim 2, further comprising:

an input waveguide including a matching network including one or more waveguide matching sections of different length and height to optimally couple the input signal, comprising an exciting electric field in the millimeter-wave, submillimeter-wave, or terahertz range, into the input antennas or E-probes within the chip while guaranteeing a broadband frequency operation; and the output waveguide including a matching network comprising one or more waveguide matching sections of different length and height to optimally couple the multiplied output signal, comprising an exciting electric field in the millimeter-wave, submillimeter-wave or terahertz range, out of the input antennas or E-probes within the chip while guaranteeing a broadband frequency operation.

4. The device of claim 3, wherein:

the input and output waveguide matching sections can be formed either on:

one or more aligned Silicon wafers using deep reactive ion etching techniques (DRIE) and subsequent gold plating, or for lower frequencies of operation, on aligned thin metal plates using traditional CNC milling techniques; and the different wafers or plates are arranged vertically, along an axis perpendicular to the chip plane, to allow for a 3D integration capability.

5. The device of claim 4, wherein:

the input and output waveguides are placed perpendicular to the chip so that the input and output E-probes are in-phase with the fundamental mode of propagation in the input and output waveguides.

6. The device of claim 4, wherein:

the chip comprises a dual on-chip power-combined frequency multiplier topology where the two multiplying structures are mirrored along a same axis, and an E-plane of the input and output waveguides is the same as the chip plane.

7. The device of claim 2, further comprising:

direct current (DC) bias lines using beamleads disposed to bias each of the Schottky diodes, wherein:
the integrated circuit and DC bias lines are connected to external bias lines that are formed directly on the silicon wafer based housing that includes a waveguide channel where the chip is located, or otherwise using wire-bonded capacitors placed on the waveguide channel.
8. The device of claim 7, wherein:
a total thickness of the device including metal DC bias lines
and the substrate for the chip is in a range of 3 micrometers-50 micrometers, and
a total dimension of the device is less than 3 millimeters by
2 millimeters.
9. The device of claim 2, wherein:
an operation frequency of the device is at a millimeter-wave,
submillimeter-wave, or terahertz range depending
on a size and structure of the Schottky diodes employed,
specific dimensions of the input and output matching
networks on-chip, and dimensions of the input and output
waveguides, and
operation bandwidth is around 17%, higher than 17%, or
lower than 17%.
10. The device of claim 2, comprising:
two independent waveguide outputs so that the device can
feed two higher frequency multiplier stages or two frequency
mixers or detectors without a need of additional
waveguide based power dividers, wherein the two waveguide
outputs can be combined using a simple waveguide Y-junction if one single output is desired.
11. The device of claim 2, wherein:
the integrated circuit includes at least one pair of the bal-
anced Schottky diodes per multiplying structure, including
at least two pairs for a dual on-chip multiplier configuration
or at least four pairs for a quad on-chip multiplier configuration; and
the Schottky diodes are nonlinear semiconductor devices
that generate one or more harmonics of the input signal
so that the input signal is multiplied up in frequency.
12. The device of claim 2, wherein the integrated circuit has
a pattern that is symmetric about at least two axes passing
through a central point of the integrated circuit.
13. A method for fabricating an integrated circuit or chip
including a Monolithic Microwave Integrated Circuit
(MMIC) on-chip power-combined frequency multiplier
device, comprising:
fabricating an integrated circuit comprising two or more
multiplying structures integrated on a single chip,
wherein each of the integrated multiplying structures are
electrically identical and fabricating each of the multi-
plying structures includes:
defining two or more Schottky diodes, wherein:
the defining of each of the Schottky diodes includes
defining a Schottky diode ohmic contact and mesa
on a substrate, and
the Schottky diodes are used as nonlinear semiconduc-
tor devices to generate harmonics out of an input
signal and produce a multiplied output signal;
forming interconnect metal comprising one or more
stripe line based input matching networks and one or
more stripe line based output matching networks, and
input and output antennas or E-probes, the one or
more stripe line based input matching networks electric-
ally connecting an input antenna or an input E-probe
to the two or more Schottky diodes in a balanced
configuration, the one or more stripe line based output
matching networks for transmitting the multiplied
output signal from the Schottky diodes to an output
antenna or an output E-probe, the input antenna or
input E-probe for receiving the input signal in the
millimeter-wave, submillimeter-wave, or terahertz
frequency range inputted on the chip, and the output
antenna or the output E-probe for transmitting the
multiplied output signal off the single chip into one or
more output waveguides each comprising a transmis-
sion line;
defining and depositing Schottky anodes using electron
beam lithography;
defining bridge metal that connects the Schottky diodes
to the interconnect metal;
passivating the integrated circuit;
etching the substrate to form a membrane layer;
depositing ground and DC bias airbridges for the Schott-
ky diodes;
attaching the chip comprising the interconnect metal and
the Schottky diodes onto a carrier wafer;
removing the substrate with a selective etch;
releasing the chip from the carrier wafer; and
assembling the chip into a plated silicon-wafer based
housing or thin metal plates-based housing;
wherein:
two or more of the input antennas or input E-probes
divided the input signal equally among the multiplying
structure with the chip;
two or more of the output antennas or output E-probes
combine the output signals at the one or more output
waveguides;
power-combining of the output signals is performed
directly on chip; and
an improvement in power-handling capabilities and output
power of a factor equal to a number of the multiplying
structures included in the chip is achieved.
14. The method of claim 13, further comprising:
forming DC bias lines on the silicon wafer based housing
or metal plates-based housing to bias the Schottky
diodes;
aligning and assembling the chip within a waveguide
housings comprising one or more silicon wafers or thin metal
plates, wherein:
the waveguide housing includes an input waveguide that
inputs an electric field on the input antennas within the chip,
the waveguide housing includes the one or more output
waveguides that receive an output electric field trans-
mitted from all the output antennas or E-probes, and
the integrated circuit is positioned in a plane perpendicular
to a longitudinal axis or E-plane of the input and output
waveguides.
15. The method of claim 14, further comprising a previous
design phase comprising, for a desired input power, efficiency
and operation frequency and bandwidth within the millime-
ter-wave, submillimeter-wave, or terahertz range:
selecting a number of the Schottky diodes, a size of each of
the Schottky diodes, and a layer structure of each of the
Schottky diodes;
designing stripline matching elements comprising the
stripline based input matching networks and the stripline
based output matching networks within the chip;
designing the input and output E-probes; and
designing input and output waveguide matching networks
for the input and output waveguides.
16. A method of fabricating a Monolithic Microwave Inte-
grated Circuit (MMIC) on-chip power-combined frequency
multiplier device, comprising:
fabricating an integrated circuit comprising two or more
multiplying structures integrated on a single chip,
wherein each of the integrated multiplying structures are
electrically identical and fabricating each of the multi-
plying structures includes:
fabricating one input antenna or input E-probe for receiving an input signal in the millimeter-wave, submillimeter-wave, or terahertz frequency range inputted on the chip,

fabricating one or more stripline based input matching networks electrically connecting the input antenna or the input E-probe to two or more Schottky diodes in a balanced configuration,

fabricating the two or more Schottky diodes that are used as nonlinear semiconductor devices to generate harmonics out of the input signal and produce a multiplied output signal,

fabricating one or more stripline based output matching networks for transmitting the multiplied output signal from the Schottky diodes to an output antenna or an output E-probe, and

fabricating the output antenna or the output E-probe for transmitting the multiplied output signal off the single chip an output waveguide transmission line comprising output waveguide matching networks; and

micro-machining a plurality of silicon wafers or thin metal plates including input and output waveguide matching networks as well as a waveguide channel where the frequency multiplier chip or integrated circuit is placed, wherein the silicon wafers or thin metal plates are aligned, stacked, and fastened together using alignment pins, screw holes or any other alignment technique;

wherein:

two or more of the input antennas or input E-probes divided the input signal equally among the multiplying structure within the chip;

two or more of the output antennas or output E-probes combine the output signals at the output waveguides transmission line,

power-combining of the output signals is performed directly on chip; and

an improvement in power-handling capabilities and output power of a factor equal to a number of the multiplying structures included in the chip is achieved.

17. The method of claim 16, further comprising:

machining one or more fastening holes in each of the silicon wafers or metal plates,

machining mount holes in one or more of the silicon wafers or metal plates for external connectors; and

obtaining one or more micro-machined silicon fasteners, if silicon wafers are used, wherein the silicon wafers are fastened together with the integrated circuit between an input waveguide and the output waveguide transmission line, by insertion of the micro machined silicon fasteners into the fastening holes in each of the wafers.

18. The method of claim 16, further comprising selecting an adequate number of the silicon wafers or metal plates, and an adequate thickness, length and width of the silicon wafers or metal plates so that all waveguide structures, alignment elements, fastening elements, connectors can fit in a minimum possible volume for compactness.

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