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(54) MILLIMETER-WAVE COUPLER FOR SEMI-CONFOCAL FABRY-PEROT CAVITY

(71) Applicant: **California Institute of Technology**, Pasadena, CA (US)

(72) Inventors: **Brian J. Drouin**, Pasadena, CA (US); **Adrian Tang**, Pasadena, CA (US); **Erich T. Schlecht**, Pasadena, CA (US)

(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

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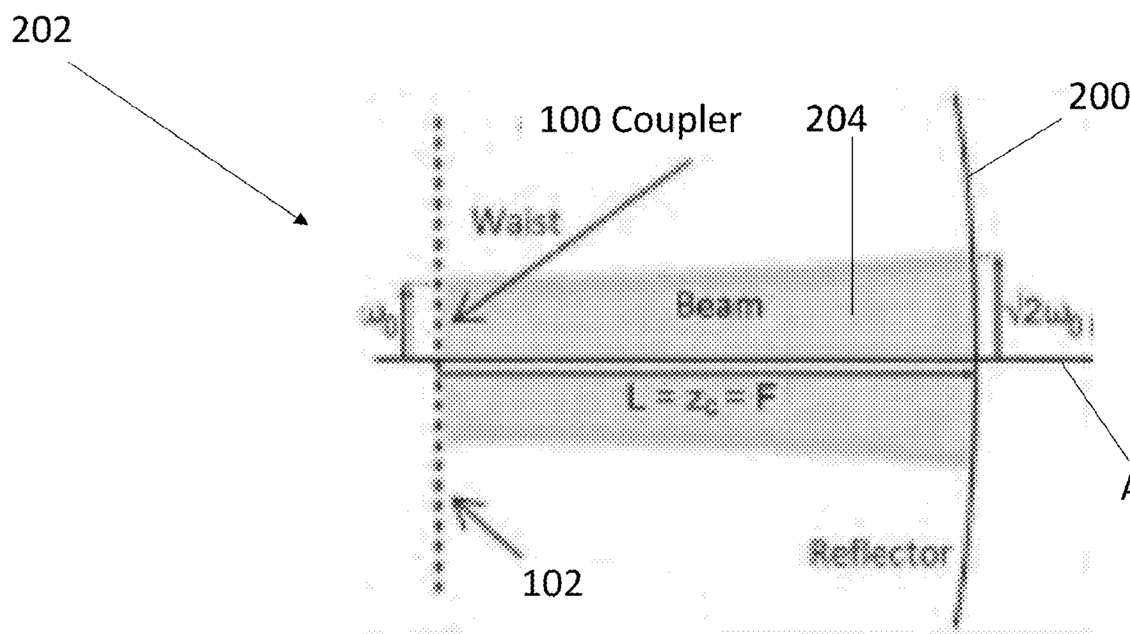
(57) **ABSTRACT**

A coupler for coupling electromagnetic radiation into a cavity, including a metal layer having a reflective surface and forming a ground plane; and one or more waveguides for gigahertz or terahertz electromagnetic radiation embedded in the metal layer. The waveguides each include two openings in the metal layer exposing a dielectric underneath; and a section of the metal layer between the two openings. A plurality of holes in the metal layer are disposed along a perimeter of the openings so as to shape the electric field of the electromagnetic radiation in a cavity coupled to the coupler.



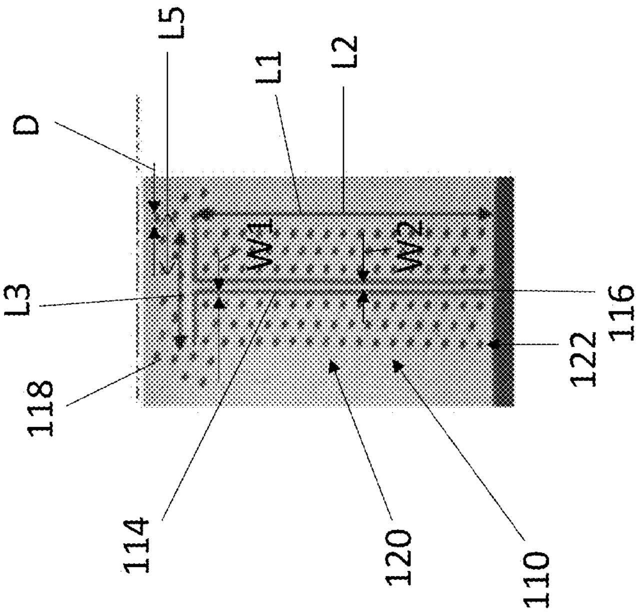

L5
D
L1
L2
L3
W1
W2
118
114
120
110
116
122

Fig. 1B

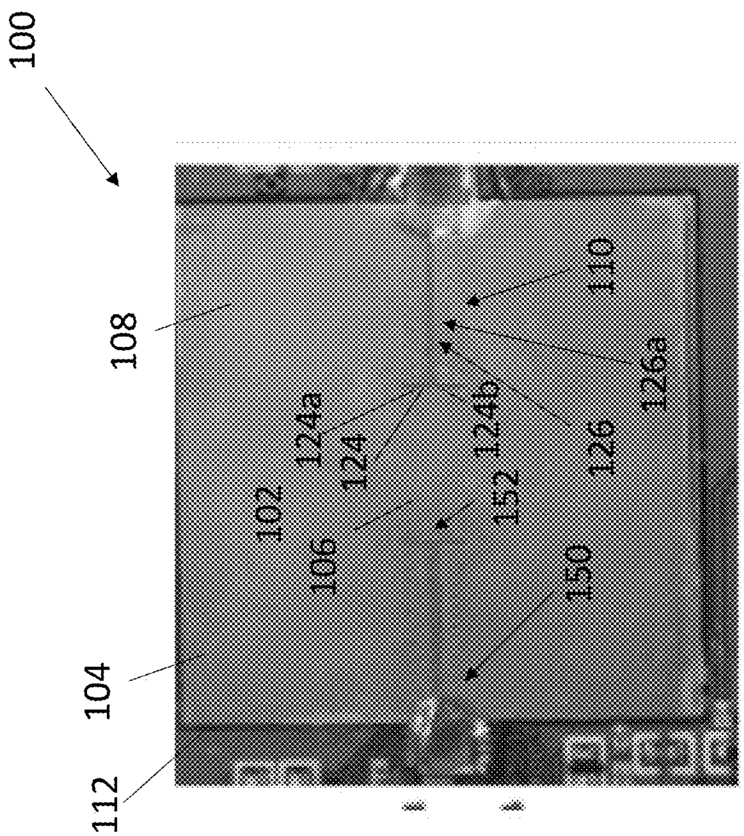
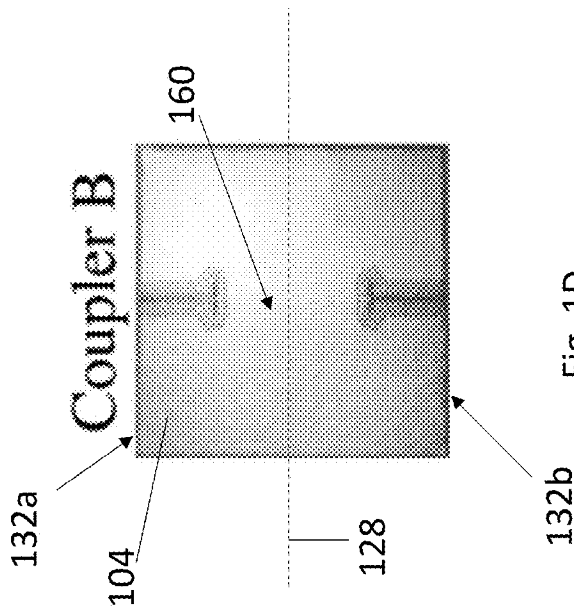
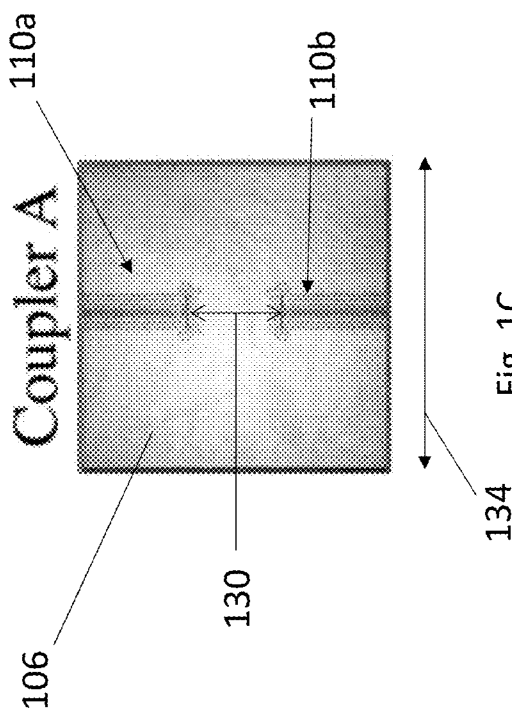

100
108
110
126a
124a
124
124b
126
102
106
152
150
104
112

Fig. 1A



Coupler B
160
132a
104
128
132b

Fig. 1D



Coupler A
110a
110b
106
130
134

Fig. 1C

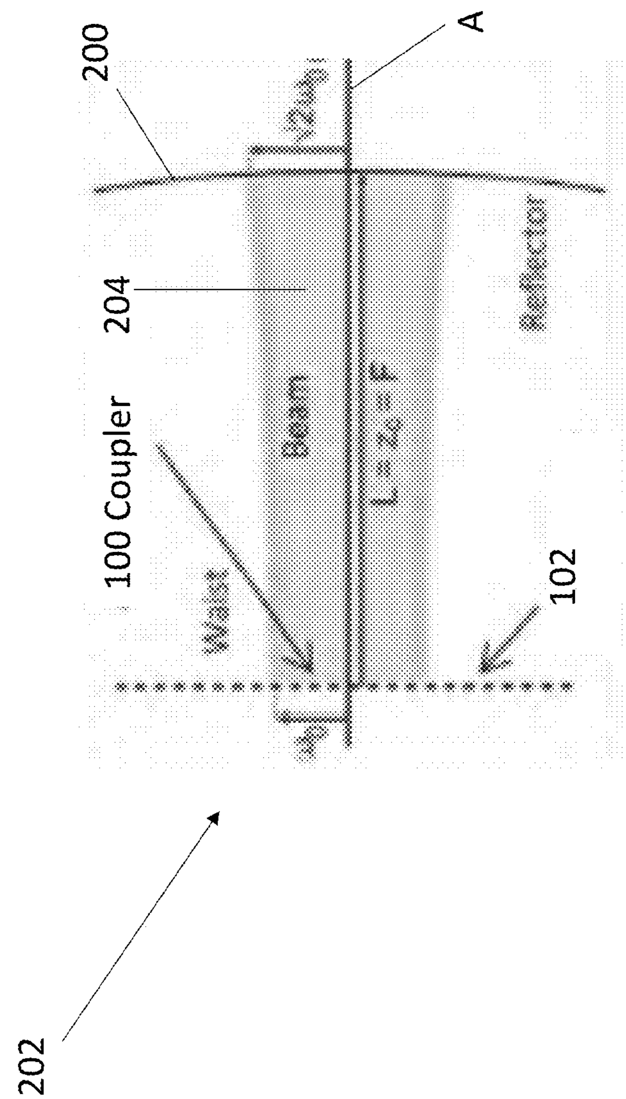


Fig. 2

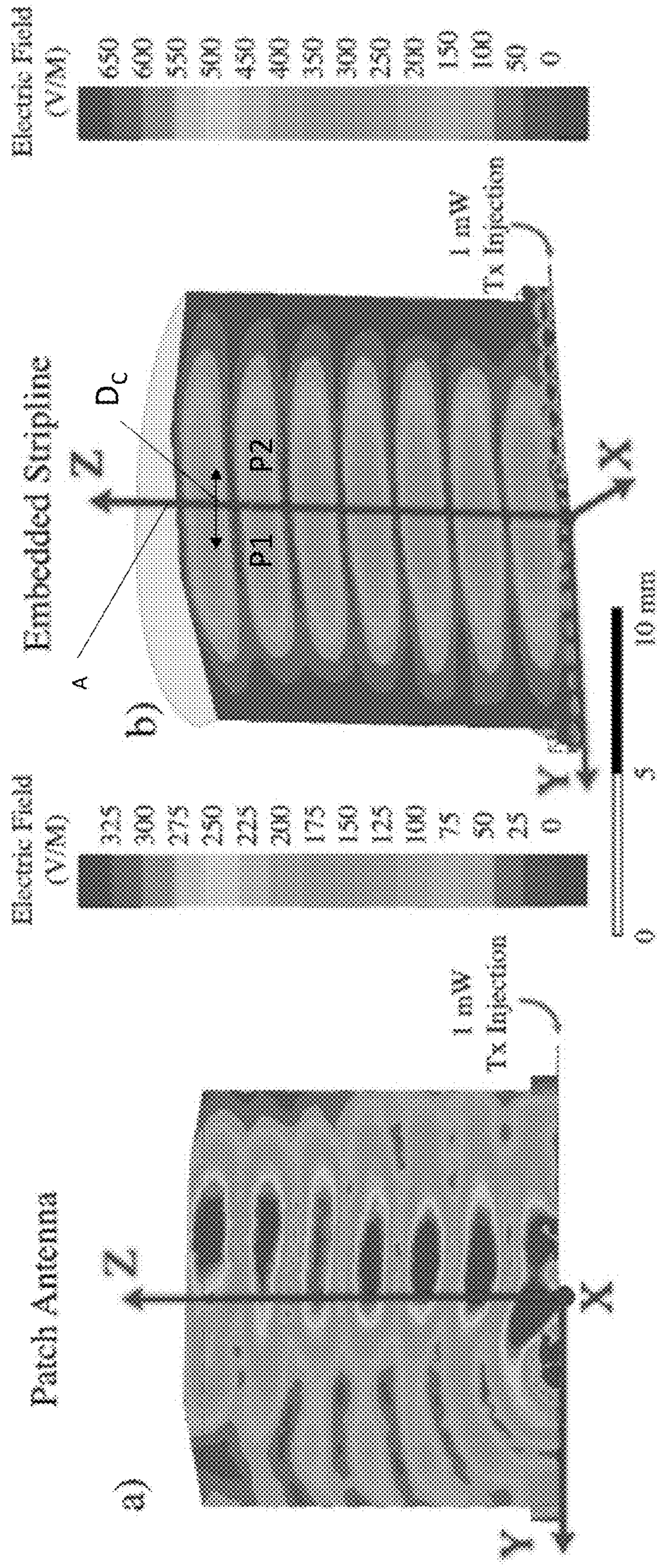

a)
Patent Antenna
Z
X
Y
1 mW
Tx Injection
Electric Field
(V/M)
325
300
275
250
225
200
175
150
125
100
75
50
25
0
0
5
10 mm
b)
Embedded Stripline
A
Z
D_C
P1
P2
X
Y
1 mW
Tx Injection
Electric Field
(V/M)
650
600
550
500
450
400
350
300
250
200
150
100
50
0

Fig. 3A

Fig. 3B

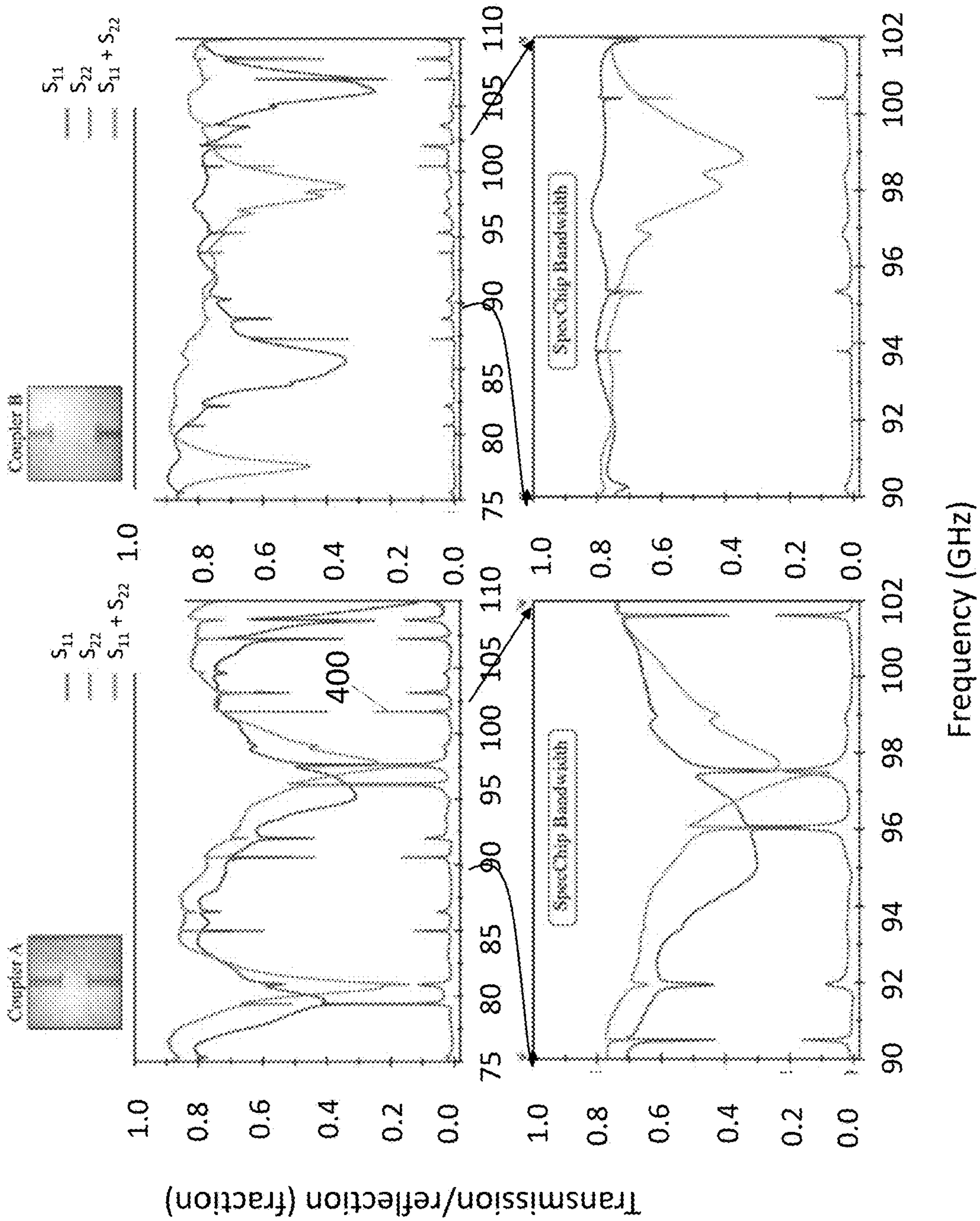


Fig. 4A

Fig. 4B

Fig. 4C

Fig. 4D

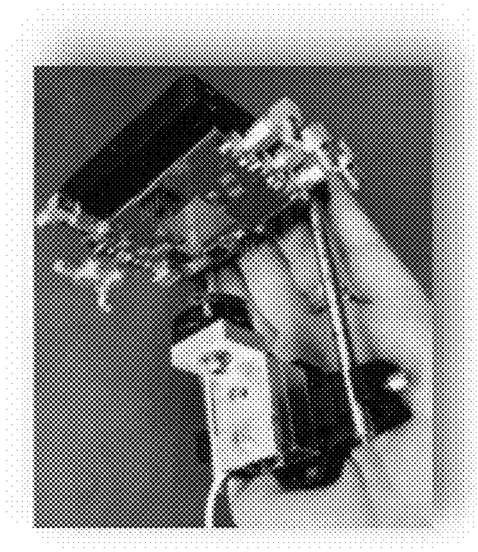


Fig. 5B

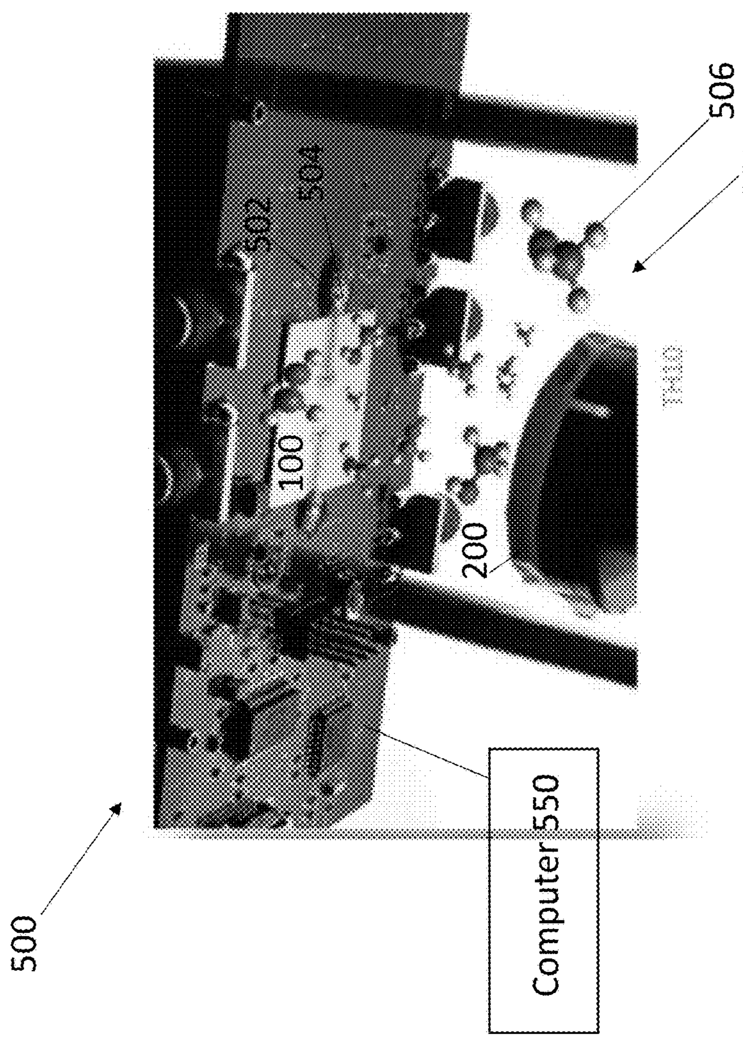


Fig. 5A

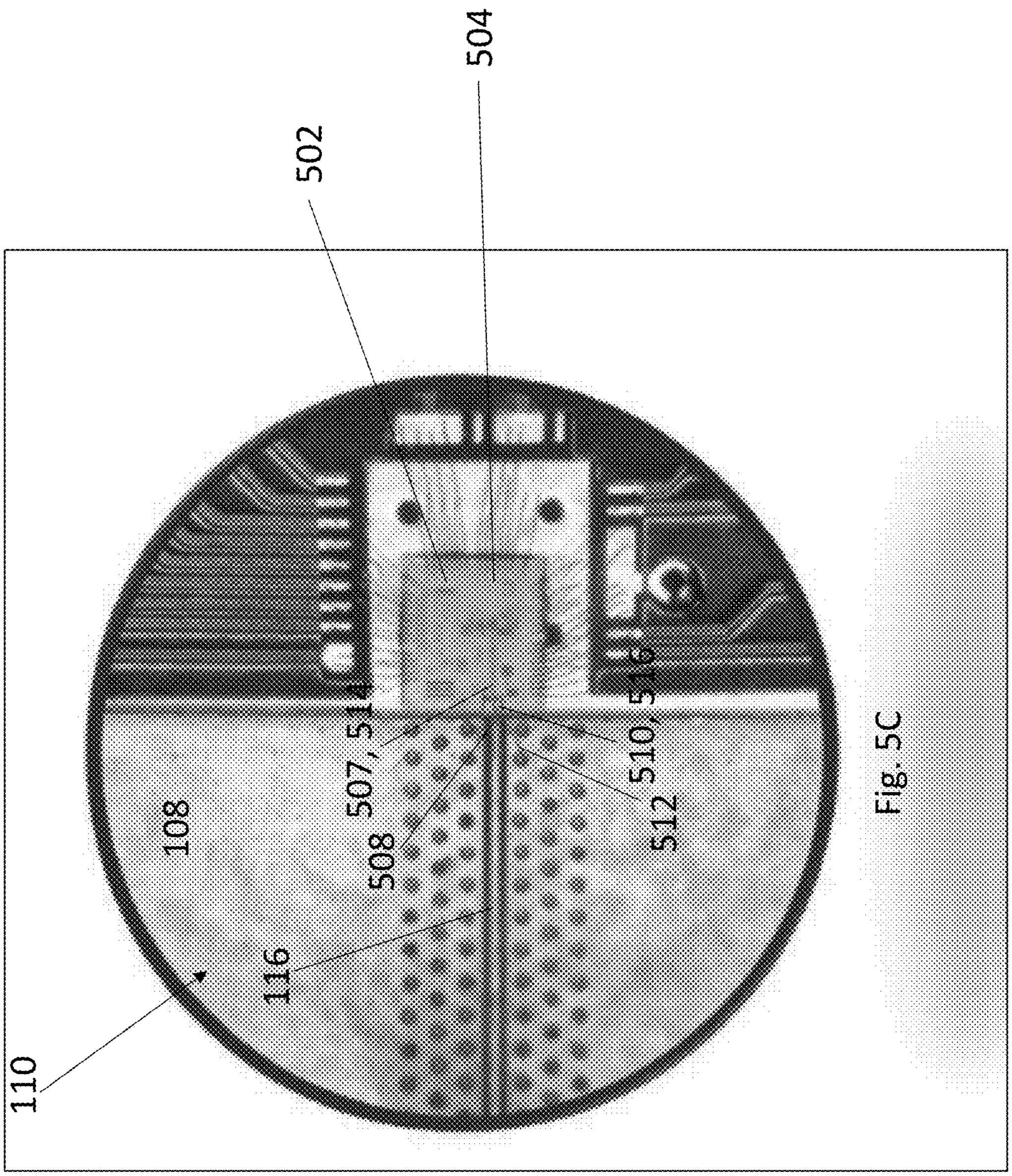


Fig. 5C

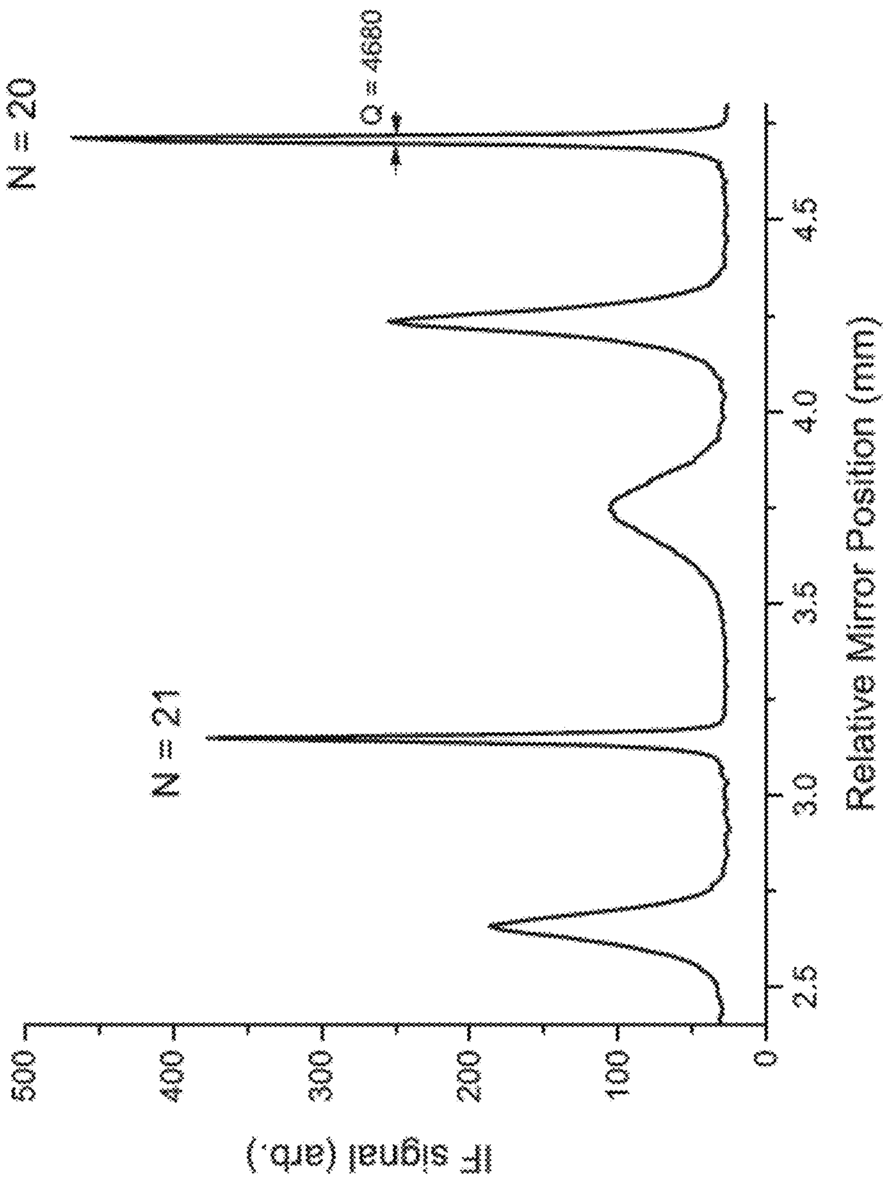

N = 20
N = 21
Q = 4680
IF signal (arb.)
0
100
200
300
400
500
2.5
3.0
3.5
4.0
4.5
Relative Mirror Position (mm)

Fig. 6

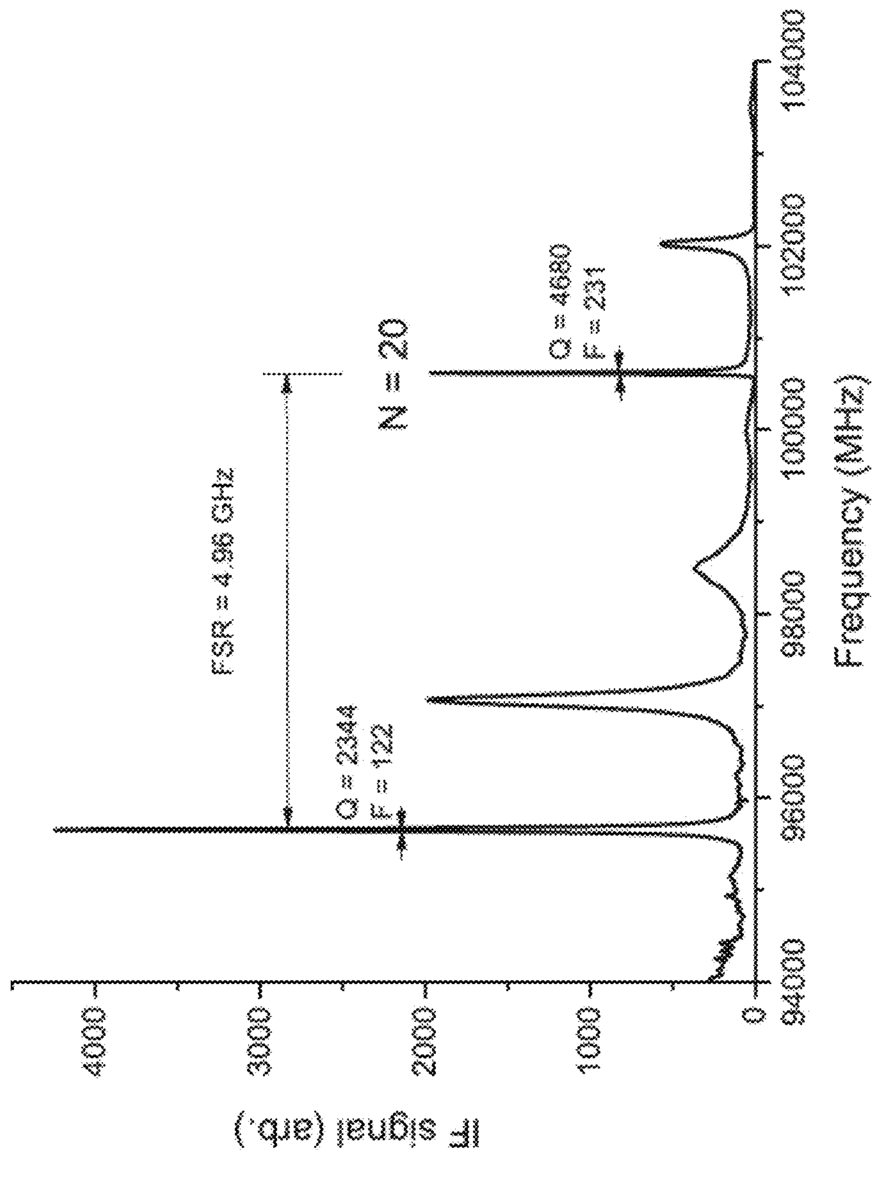

IF signal (arb.)
0
1000
2000
3000
4000
94000
96000
98000
100000
102000
104000
Frequency (MHz)
FSR = 4.96 GHz
Q = 2344
F = 122
N = 20
Q = 4680
F = 231

Fig. 7

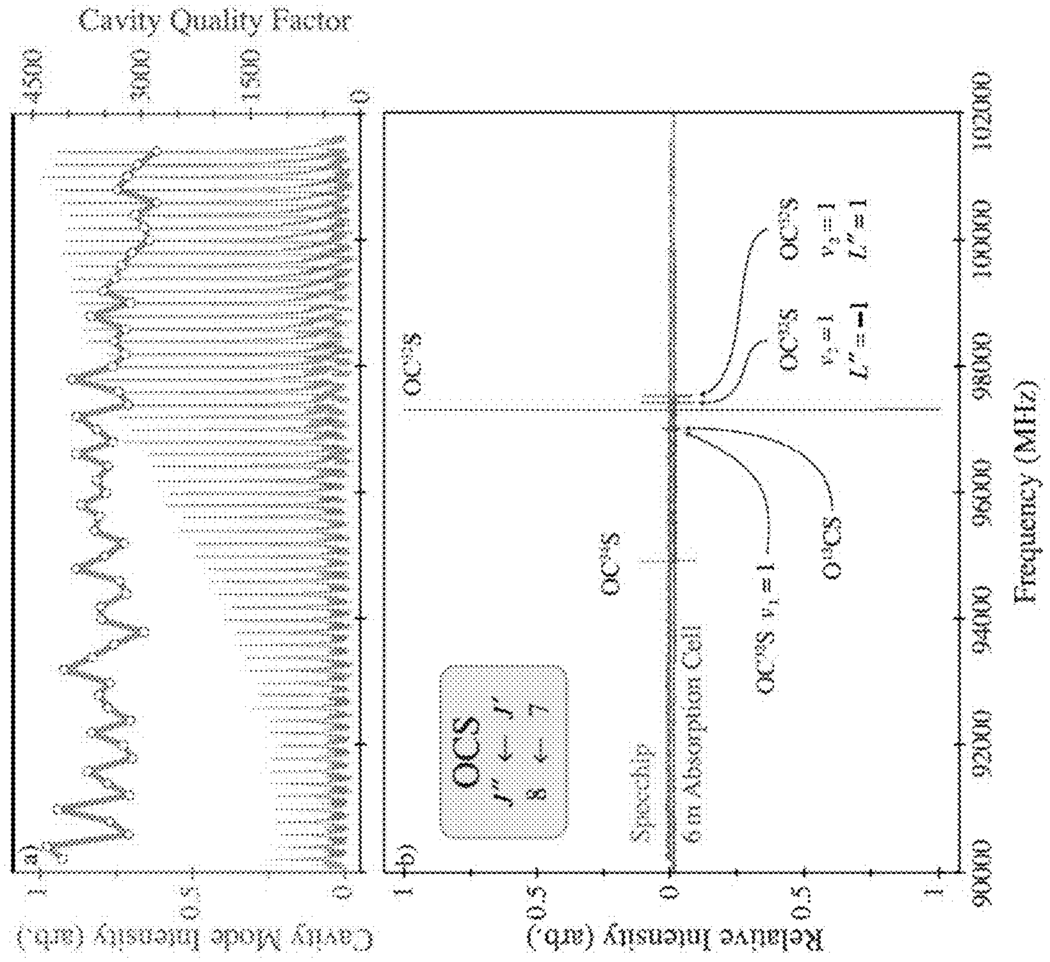

Cavity Quality Factor
Cavity Mode Intensity (arb.)
Relative Intensity (arb.)
Frequency (MHz)
OCS
Spectchip
6 m Absorption Cell

Fig. 8

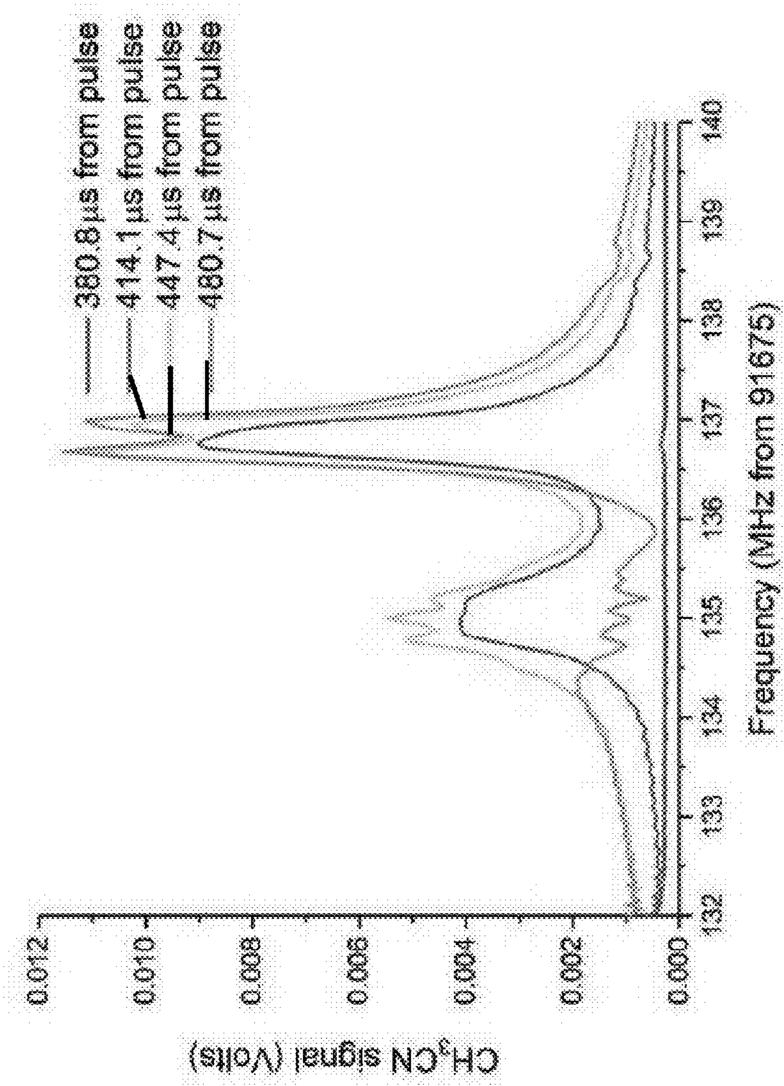

380.8μs from pulse
414.1μs from pulse
447.4μs from pulse
480.7μs from pulse
CH3CN signal (Volts)
0.012
0.010
0.008
0.006
0.004
0.002
0.000
132
133
134
135
136
137
138
139
140
Frequency (MHz from 91675)

Fig. 9

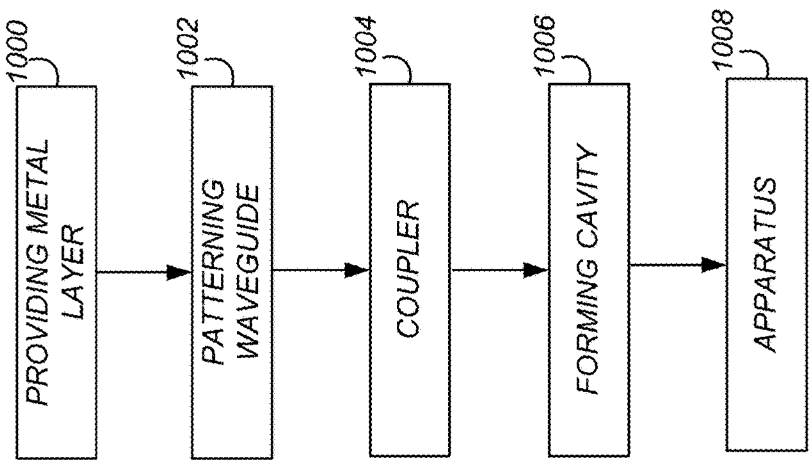

1000
PROVIDING METAL LAYER
1002
PATTERNING WAVEGUIDE
1004
COUPLER
1006
FORMING CAVITY
1008
APPARATUS

Fig. 10

MILLIMETER-WAVE COUPLER FOR SEMI-CONFOCAL FABRY-PEROT CAVITY

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. Section 119(e) of co-pending and commonly-assigned U.S. Provisional Patent Application Ser. No. 62/540,710, filed on Aug. 3, 2017, by Erich T. Schlecht, Adrian J. Tang, Theodore J. Reck, Brian J. Drouin, Deacon J. Nemchick, and Alexander W. Raymond, entitled "MILLIMETER-WAVE COUPLER FOR SEMI-CONFOCAL FABRY-PEROT CAVITY," (CIT-7826-P), which application is incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] The invention described herein was made in the performance of work under a NASA contract NNN12AA01C, 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

[0003] This invention relates to a method and system for gas identification and quantification.

2. Description of the Related Art

[0004] (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.)

[0005] Many applications require the detection of small molecular tracers and determination of their abundance and origin. For detections in the gas phase, the rotational spectrum of a polar molecule typically provides a strong interaction with centimeter and shorter wavelength radiation, which has been exploited for remote sensing for half a century with data repositories growing to support the widespread efforts [2,3]. In situ instruments are now being developed [4,5] but have lagged behind remote sensors due to the large equipment traditionally required for generation and detection of this radiation. These first generation instruments are man-portable, but not yet compact enough for many practical applications. Moreover, while cavity resonators have been fabricated for detection in the millimeter [7] and submillimeter [8] range, their use in the millimeter range has been hampered due to difficulties with coupling radiation efficiently into high finesse cavities.

SUMMARY OF THE INVENTION

[0006] To overcome the limitations in the art described above, and to overcome other limitations that will become apparent upon reading and understanding this specification, the present disclosure describes a coupler for coupling electromagnetic radiation having a wavelength λ (e.g., at band center) into a cavity. The coupler includes a metal layer having a reflective surface, the metal layer forming a ground plane; and one or more waveguides for gigahertz or terahertz electromagnetic radiation embedded in the metal layer.

[0007] The waveguides each include two openings in the metal layer exposing a dielectric under the metal layer; and a section of the metal layer between the two openings. A plurality of holes are disposed in the metal layer along an edge of the openings so as to smooth out an electric field of the electromagnetic radiation confined in the cavity.

[0008] The coupler can be embodied in many ways including, but not limited to, the following examples.

[0009] 1. The coupler wherein the holes are disposed around a perimeter of the waveguide.

[0010] 2. The coupler wherein the holes are disposed in a hexagonal pattern.

[0011] 3. The coupler of one or any combination of the previous examples wherein the holes have a diameter or a width in a range of λ/15-λ/5 or 200-600 micrometers.

[0012] 4. The coupler of one or any combination of the previous examples wherein the holes are separated by a distance in a range of λ/5-λ/2 or 600-1500 micrometers (distance from a center of one hole to a center of an adjacent hole)

[0013] 5. The coupler of one or any combination of the previous examples wherein the holes are disposed in 2-4 rows.

[0014] 6. The coupler of one or any combination of the previous examples, wherein the openings in the waveguide have a width in a range of λ/5-λ/2, where λ is the wavelength at band center, or 600-1500 micrometers in the demonstration.

[0015] 7. The coupler of one or any combination of the previous examples, wherein the openings each have an L shape having a base portion and a back portion.

[0016] 8. The coupler of example 7, wherein the base portion has a length in a range of λ/2-4λ, or 1-4 mm and the back portion has a length in a range of 3λ-15 λ, or 5-15 millimeters (mm).

[0017] 9. The coupler of example 7 or 8, wherein the L shapes are positioned symmetrically about the section of the metal layer so as to form mirror images of each other with respect to the section of the metal layer.

[0018] 10. The coupler of one or any combination of the previous examples, further comprising two of the waveguides embedded in the metal layer, wherein each waveguide is a mirror image of the other waveguide about an axis of symmetry of the metal layer.

[0019] 11. The coupler of example 10, wherein the openings each have an L shape having a base portion and a back portion; the L shapes in each waveguide are positioned symmetrically about the section of the metal layer so as to form mirror images of each other with respect to the section of the metal layer, and a perpendicular distance between the base portions, in one of the waveguidesr, to the base portions in the other waveguide in the pair, is in a range of λ/2-3 λ or 2-10 mm in the demonstration.

[0020] 12. The coupler of example 11, wherein the reflective surface is rectangular and has sides having a length in a range of 3λ-15 λ, or 10-50 mm in this demonstration.

[0021] 13. The coupler of example 11, wherein the reflective surface is rectangular and has a first side opposite a second side, the first side and the second side each having a length in a range of 3 λ-15 λ, or 10-50 mm in this demonstration; the waveguides include a first waveguide and a second waveguide, the openings and the section in the first waveguide extend to the first side, and the openings and the section in the second waveguide extend to the second side.

[0022] 14. The coupler of one or any combination of the previous examples, wherein the waveguides each comprise a stripline including the section of metal between two sections of the ground plane.

[0023] 15. The coupler of one or any combination of the previous examples, wherein the coupler is coupled to a second mirror so as to form a cavity confining the electromagnetic radiation and generating modes of the electromagnetic radiation in the cavity when the electromagnetic radiation is coupled into the cavity through the one or more waveguides coupler. The modes comprise peaks and troughs of a cavity electric field evenly spaced along the cavity's longitudinal axis, and the cavity electric field is symmetrically distributed in at least one direction perpendicular to the cavity axis.

[0024] 16. The coupler of example 15, wherein the cavity electric field at a first point and a second point symmetrically positioned on either side of the cavity's axis are the same to within 10%.

[0025] 17. The coupler of example 16, wherein the first point and the second point are each at a same distance in a range of λ-3 λ, 3-10 mm in this demonstration, from the axis.

[0026] The coupler is comprised of a slot (the short legs of the "Ls") that radiates the signal into the semi-confocal resonator. It radiates due to an electric field across the slot that is excited by a short "stub" antenna that receives the signal from the transmitter along a coplanar waveguide (CPW) transmission line (the two parallel long legs of the "L"s). The cluster of via holes confines the signal to the CPW line and the slot, preventing it from leaking into the dielectric region under the top ground plane. The second slot works in reverse to convey the resonator signals to the receiver.

[0027] The coupler radiates only weakly into the resonator, requiring several hundred cycles of the signal to build up the electric field in the resonator to its peak value. This is required to enable the resonator to have the high quality factor necessary for operation: the reciprocity principle of electromagnetism dictates that a more efficient radiator would also allow the signal to leak prematurely back into the CPW lines to the transmitter and receiver.

[0028] The present disclosure further describes a spectrometer including the coupler of one or any combination of the examples described above. The spectrometer includes a transmitter coupled to the coupler, wherein the transmitter transmits an electric field to the coupler and the electric field is transmitted along the waveguide and generates the electromagnetic radiation outputted from the coupler into the cavity. The spectrometer further includes a receiver coupled to the coupler for receiving an output electric field transmitted along the waveguide in response to a presence of a molecule in the cavity interacting with the cavity electrical field of the electromagnetic radiation. A computer coupled to the receiver determines a composition of the molecule from the output electric field.

[0029] In one or more examples, the transmitter includes a first output electrically connected to the center section of the waveguide at a side of the metal layer; and a second output electrically connected to the ground plane at the side of the metal layer so as to apply an electrical field across the section and the ground plane. The spectrometer further includes a receiver including a first input electrically connected to the section of the waveguide at the side of the metal layer, and a second input electrically connected to the ground plane so as to receive the output electrical field applied across the section of the waveguide and the ground plane in response to the molecule in the cavity interacting with the cavity electrical field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

[0031] FIG. **1**A illustrates a coupler according to one embodiment of the present invention.

[0032] FIG. **1**B illustrates a waveguide embedded in the coupler, according to one or more embodiments of the present invention.

[0033] FIG. **1**C and FIG. **1**D illustrate couplers with different waveguide lengths, according to one or more embodiments, wherein FIG. **1**C illustrates a coupler with a waveguide having a 2λ, 7 mm in this example, length (coupler A) and FIG. **1**D illustrates a coupler with a 1.5λ, 5 mm in this example, length (Coupler B). The waveguides in FIGS. **1**C and **1**D are both terminated with ¾ λ, 2.5 mm in this example, wide edges.

[0034] FIG. **2** illustrates a cavity including the coupler, according to one or more embodiments.

[0035] FIG. **3**A-**3**B. Two dimensional slice of simulated results highlighting drastically different coupler emission properties for patch antenna (FIG. **3**A) and embedded coplanar waveguide (FIG. **3**B) test designs. In both examples, 1 mW of continuous wave radiation is injected into the right side of the coupler plate, which is positioned in the XY plane. An optical cavity is established with a concave reflector (not depicted) that is positioned 10 mm away from the coupler normal to the Z-axis.

[0036] FIGS. **4**A-**4**D. The S-parameters obtained from VNA measurements are plotted for all of W-band (FIG. **4**A, **4**B) and expanded for the SpecChip bandwidth (FIG. **4**C, **4**D). The data for Coupler A (FIG. **1**C) is shown in FIGS. **4**A, **4**C; the data for Coupler B (FIG. **1**D) is shown in FIGS. **4**B and **4**D. Reflections off the input (S**11**) and output (S**22**) are typically 80%, but periodic drops to as low as 20% are observed. When both the transmitter and receiver have low reflections at the same wavelengths (FIG. **4**A, **4**C), transmission (S**12**/S**21**) is boosted; however, the cavity is less isolated, causing the finesse (and Q-factor) to drop.

[0037] FIG. **5**A illustrates a spectrometer including the coupler according to one or more embodiments.

[0038] FIG. **5**B illustrates the spectrometer including the coupler and a translation stage, according to one or more embodiments.

[0039] FIG. **5**C illustrates a transmitter (TX) attached to the coupler, according to one or more embodiments. The receiver (not shown) is attached in analogous fashion.

[0040] FIG. **6** illustrates results of a Mirror position scan over 2 mm (λ/2 at 100.5 GHz is 1.49 mm) displaying primary (TEM00 with sharp narrow features), secondary (TEM01 intermediate features), and a tertiary TEM02 mode.

[0041] FIG. **7** illustrates a frequency scan over 10 GHz displaying primary (TEM00 with sharp narrow features), secondary TEM01 (intermediate features) and a broad tertiary TEM02 mode. The free spectral range is 4.96 GHz and the primary modes have quality factors (Q) of 2344 and 4680 and finesses (F) of 122 and 231 at lower and higher frequencies, respectively.

[0042] FIG. **8**. Evolution of a single cavity mode (a) tracked across the bandwidth of the SpecChip instrument outfitted with a 50 mm focal length, f=50 mm, 50 mm diameter, φ=50 mm end mirror, 50 mm corresponds to 15 λ at band center. Each mode was fit with a Lorentzian line shape to extract cavity quality factors which are also plotted. The bottom panel depicts bulk, 3 mTorr, OCS survey scans taken with the pulsed SpecChip instrument (green) and with a traditional frequency-modulated absorption spectrometer (purple).

[0043] FIG. **9** spectrum obtained using the spectrometer including the coupler, according to one or more examples.

[0044] FIG. **10** is a flowchart illustrating a method of making a coupler, according to one or more examples.

DETAILED DESCRIPTION OF THE INVENTION

[0045] 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.

[0046] Technical Description

[0047] Coupler Example

[0048] FIG. **1**A illustrates a coupler **100** for electromagnetic radiation, comprising a metallic (e.g. gold, copper) mirror or reflector **102**, that constitutes or comprises also the grounded co-planar waveguide elements; i.e. one or more waveguides **110** for gigahertz or terahertz electromagnetic radiation embedded in a metal layer **104** that includes a ground plane **108** and has a reflective surface **106**. The metal layer **104** is deposited on a substrate (e.g., a dielectric **112** such as Duroid). Examples of electromagnetic radiation include, but are not limited to, electromagnetic radiation having a wavelength, λ (e.g., at band center), between 0.5-5 mm. Examples of electromagnetic radiation include, but are not limited to, electromagnetic radiation having a frequency between 0.06 and 0.6 Terahertz, or 60-600 Gigahertz. The coupler **100** further includes the main ground plane (not shown) under the substrate.

[0049] FIG. **1**B further illustrates each of the waveguides **110** include two openings **114** or slots in the metal layer exposing a dielectric **112** underneath; and a (e.g., rectangular) section **116** (e.g., strip) of the metal layer between the two openings. Example dimensions for the openings include, but are not limited to, a width W**1** in a range of λ/5-λ/2, 600-1500 micrometers in this example, and a length L**1** in a range of 1.5 λ-15 λ, 5-15 mm in this example. Example dimensions for the strip **116** include, but are not limited to, a width W**2** in a range of λ/5-λ/2 or 600-1500 micrometers and a length L**2** in a range of 3 λ-15 λ or 5-15 mm. In the example of FIGS. **1A-1**B, the waveguide **110** is a stripline including the section of metal between two sections of the ground plane **108**.

[0050] FIG. **1**B further illustrates a plurality of holes **118** are disposed in the metal layer along an edge of the openings. The holes expose the dielectric under the metal layer. In one or more examples, the holes are disposed around a perimeter of the waveguide. In one or more further examples, the holes are disposed in pattern including, but not limited to, a hexagonal pattern **120** or rows **122** (e.g., 2-4 rows). Example dimensions for the holes include, but are not limited to, a diameter D or a width in a range of λ/15-λ/5 or 200-600 micrometers. Example hole spacings include, but are not limited to, a spacing in a range of λ/5-λ/2 or 600-1500 micrometers (distance from a center of one hole to a center of an adjacent hole) and are dependent on the chosen substrate which is not necessary the Duroid depicted in the example.

[0051] In the example illustrated in FIGS. **1**A and **1**B, the openings **114** each have an L shape having a base portion **124** and a back portion **126** wherein the L shapes are positioned symmetrically about the section of the metal layer so as to form mirror images of each other with respect to the section of the metal layer. Example dimensions of the base portion are such that a length L**3** (the sum of the lengths of two base portions **124** and the strip width W**2**) is a range of λ/2-4 λ, or 1-4 mm. Example dimensions of the back portion include, but are not limited to, a length L**1**, L**2** in a range of 3 λ-15 λ, or 5-15 mm.

[0052] In the examples illustrated in FIG. **1**C and FIG. **1**D, the coupler **100** includes two (a pair of) waveguides **110***a*, **110***b* embedded in the metal layer **104** so that each waveguide **110***a*, **110***b* is a mirror image of the other waveguide about an axis of symmetry **128** of the metal layer. FIG. **1**C illustrates a coupler with a waveguide having a length L**2**=7 mm (coupler A) and FIG. **1**D illustrates a coupler with a length L**2**=5mm length (Coupler B). The waveguides in FIGS. **1**C and **1**D are both terminated with L**3**=2.5 mm wide edges. In one or more examples, a perpendicular distance **130** between the base portions **124**, in one of the waveguides **110***a* in the pair, to the base portions in the other waveguide **110***b* in the pair, is in a range of λ/2-3λ or 2-10 mm in this demonstration.

[0053] FIGS. **1**C and FIG. **1**D further illustrate an example wherein the reflective surface **102** is rectangular (square) and has sides **132***a*, **132***b* having a length **134** in a range of λ-15 λ, or 10-50 mm in this demonstration. The openings **114** and the section **116** in the first waveguide **110***a* extend to the first side **132***a*, and the openings **114** and the section **116** in the second waveguide **110***b* extend to the second side **132***b* opposite the first side **132***a*.

[0054] Example Coupler Design for Use in a Cavity

[0055] The development of an efficient coupler plate was achieved by running full electromagnetic field simulations on a series of test designs using the high-frequency simulation software (HF SS) package by ANSYS. This analysis tool allows for the visualization of cavity mode structures as well as graphical display of transmitted power and phase rotation. Due to the computationally intensive calculations required for fully modeling the coupler plate waveform in three dimensions, the mode structures were calculated with a concave mirror at a closer distance (10 mm) than those used (25 mm or 50 mm) for the experimental demonstration examples described herein.

[0056] FIG. **2** illustrates the coupler **100** coupled to a second mirror **200** so as to form a cavity **202** confining electromagnetic radiation **204**. The mode structures (from TEMnm, n,m=0,1,2, . . .) were found to be strongly dependent on (1) the distance **130** between the coupler feeds (waveguides **110**), which extend from the edges of the planar mirror **102** where the chips (transmitter **302** and receiver

304) are mounted, to a central, completely reflective region; (2) the positioning of via holes **118** that shape the beam **204** as it exits or enters the plane; (3) the distance to and diameter of the spherical mirror **200**, which allows preferential discrimination against higher order modes (n,m>0).

[0057] Initial attempts using traditional patch antenna designs, where an example simulation is depicted in FIG. **3**A, produced unsatisfactory results with mode structures found to be off-axis with respect to the optical cavity and responses found to vary dramatically across the instrument bandwidth. The coupler illustrated in FIGS. **1**A, **1**B, **1**C, and **1**D, on the other hand, including carefully positioned "via" holes **118** paired with coplanar waveguides **110** to which the transmitter can be wire bonded directly, was found to provide a balanced response independent of the injected radiation wavelength, see FIG. **3**B. Specifically, FIG. **3**B illustrates the coupler coupled to a second mirror forms a cavity confining the electromagnetic radiation and generating modes of the electromagnetic radiation in the cavity when the electromagnetic radiation is coupled into the cavity through the one or more waveguides. The modes comprise strong field regions (peaks) that can interact with a molecule, and troughs/nodes of a cavity electric field, wherein the peaks and nodes are evenly spaced along the cavity's longitudinal axis A. Moreover, the cavity electric field is symmetrically distributed in at least one direction perpendicular to the cavity axis. In one or more examples, symmetry of the cavity electric field is characterized by the cavity electric field at a first point P**1** and a second point P**2** symmetrically positioned on either side of the cavity's axis A being the same to within 10% (e.g., when the first point P**1** and the second point P**2** are each at a same distance in a range of λ-3 λ, or 3-10 mm in this demonstration, from the axis). The holes are disposed around the perimeter of the waveguide so as to inject the radiation deep into the central portion of the coupler (achieving some isolation) and to establish the symmetrical distribution of the cavity electric field.

[0058] Copper-plated Duroid coupler structures achieving the field profile of FIG. **3**(*b*) were fabricated (as shown in FIG. **1**C and **1**D) and tested. To test the performance properties of the fabricated coupler designs, freestanding units were constructed consisting of a coupler plate mounted onto an aluminum base with wire probes used to connect the embedded coplanar waveguides to standard WR10 waveguide flanges for interfacing with standard mm-wave laboratory equipment. An optical cavity, as illustrated in FIG. **2**, was established/aligned with a kinematic mounted concave mirror and translation stage. Measurements with a W-band vector network analyzer (VNA) (instead of a CMOS Tx/Rx integrated circuit), time gated to remove the influence of waveguide coupling, were performed to provide insight into the input (S_{11}) and output (S_{22}) reflection properties as well as total transmission (S_{12}/S_{21}) of the isolated coupler. A subset of these measurements is plotted in FIGS. **4**A-**4**D which show that the input and output reflections are largely symmetric, although having a frequency shift hinting at fabrication asymmetries.

[0059] A molecule having electromagnetic transition defined by energy levels separated by an energy E=hν can interact with electromagnetic radiation having a frequency ν. In a cavity, energy of the electromagnetic radiation can be resonantly transferred into the molecule. The resonant transfer results in transient absorption and subsequent emission that is characteristic to the molecule. The efficiency and lifetime of the resonant transfer of energy is in part determined by the linewidth of the cavity modes (transmission peaks **400**) illustrated in FIG. **4**A-**4**B (larger linewidths indicating shorter lifetime of the cavity electric field in the cavity and therefore weaker coupling to molecular electromagnetic transitions shorter lifetimes/reduced efficiency for the resonant transfer). FIG. **4**A and FIG. **4**B illustrate linewidths that are (surprisingly and unexpectedly) 10 times narrower than predicted by simulations, indicating that the coupler enables significantly stronger interaction between the molecule and the electromagnetic radiation. As a result, molecular compositions can be extracted from cavity absorption spectra with accuracy and efficiency.

[0060] FIGS. **4**A-**4**D further illustrates that the length L**2** of the waveguides **110** can be tuned to control the amount of electromagnetic radiation energy inputted into the cavity **202**. Coupler A (FIG. **1**C) having the shorter waveguide length L**2** (as compared to coupler B shown n FIG. **1**D) coupled a larger amount of electromagnetic radiation that was confined in the cavity for a longer period of time (as evidenced by the taller resonance peaks **400** in FIG. **4**A as compared to FIG. **4**B).

[0061] In one or more examples it is desirable to maximize the amount of energy inputted into the molecules interacting with the cavity electric field. However, there is a quantum limit to the amount of energy that can be inputted into the molecules (excess amounts of energy inputted into the cavity beyond the quantum limit are not resonantly transferred between the molecule and the cavity electric field; instead, the excess energy induces a coherent, non-emissive state that reduces sensitivity. As illustrated herein, the amount of energy coupled to the molecules can be tailored depending on the molecule and cavity by tuning the coupler (e.g., tuning lengths L**2**/L**3** of the waveguides **110**). In one or more embodiments, the lengths L**2** and/or L**3** of the waveguides **110**, as well as the timing controls of the injected radiation, are tailored so that an amount of energy transferred to a molecule in the cavity **202** from the electromagnetic radiation **204** inputted into the cavity **202**, does not exceed a quantum limit. In one or more embodiments, the lengths L**2** and L**3** are tailored so that cavity's mode-width is wider than the targeted absorption feature of the molecule being analyzed.

[0062] The Q-factors extracted from the transmission trace ranged from 1000 to 4000 across all of W-band, a finding which is in alignment with the results observed in the spectrometer system (cf., FIG. **8**) over its narrower functioning bandwidth. After VNA testing, couplers having the desired balance between cavity quality factors, injection power, and isolation were selected for circuit board integration.

[0063] Example Spectrometer for Measuring the Composition of a Molecule

[0064] In this example, the coupler mounted with waveguide access was used to create a pulsed Fourier-transform millimeter-wave spectrometer. Additional uses of this coupler may include, but are not limited to, a tunable THz radiation filter or a passive amplifier for free-space coupling.

[0065] FIGS. **5**A-**5**B illustrate a spectrometer **500** including the coupler **100**, the cavity **202**, and a transmitter **502** and receiver **504** coupled to the coupler. The transmitter transmits an input electric field to the coupler and the input electric field is transmitted along the waveguide **110** so as to generate the electromagnetic radiation **204** outputted from the coupler into the cavity **202**. In one or more examples, the input electric field is inputted at a first end **150** of the waveguide **110** and the input electric field transmitted along the waveguide generates the electromagnetic radiation **204** radiating from a second end **152** of the waveguide at the base portion **124**. The electromagnetic radiation **204** is confined in the cavity by reflecting between the reflective surface **106** of the metal layer **104**, including at central region **160** of the reflective surface **106** between the waveguides **110**, and the second mirror **200**.

[0066] The receiver **504** coupled to the coupler **100** receives an output electric field transmitted along the waveguide in response to a presence of a molecule **506** in the cavity interacting with the cavity electrical field of the electromagnetic radiation **204**. A computer **550** coupled to the receiver **504** determines a composition of the molecule from the output electric field.

[0067] FIG. **5**B illustrates an example wherein, to create a high-finesse cavity mode structure with the coupler circuit, a round, gold-plated, spherical mirror with 2.5 cm focal length is mounted on a precision translation stage (PI MikroMove stage providing submicron translations) approximately three cm above the coupler and fixed along the perpendicular axis projected from the coupler's central area.

[0068] FIG. **5**C illustrates the transmitter **502** includes a first output **507** electrically connected (e.g., via wire **508**) to the section/strip **116** at the side **132***a* of the metal layer; and a second output **510** electrically connected (e.g. via wire **512**) to the ground plane **108** at the side **132***a*. The first output **507** and second output **510** apply the input electrical field between the section/strip **116** and the ground plane **108**. The receiver **504** includes a first input **514** electrically connected (e.g., via wire **508**) to the section/strip **116** at the side **132***a* and a second input **516** electrically connected (e.g. via wire **512**) to the ground plane **108**. The first input **514** and the second input **516** receive the output electrical field applied between the section/strip **116** and the ground plane **108** in response to the molecule **506** in the cavity **202** interacting with the cavity electrical field.

[0069] In one or more examples, the spectrometer system includes PCB-mounted source and detection electronics including a chip-based RF synthesizer (SiLab 5340b, 3 W) and the two custom CMOS chips (0.3 W). In one or more examples, the chips (transmitter and receiver) and coupler are embedded on a custom printed circuit board along with an Atmega processor and universal serial bus interface. A command/control program developed for operations of both the Tx and Rx chips can be loaded onto the processor and simple commands can be used to adjust pulse lengths, amplifier gains, or dispatch several algorithms used to automatically lock the synthesizers. In one or more examples, both Tx and Rx chips have embedded synthesizers tunable in the 92-104 GHz range, these initial checkouts utilize an external source generator that is more finely tunable (<1 kHz tuning possible at 92-104 GHz). Combined with the space requirements of the piezo-mounted end mirror, the device illustrated in FIG. **5**B occupies only ~1 liter of total volume.

[0070] For the measurements described herein, the reflexive coupler was designed onto the surface of a gold-plated circuit board that can also act as a flat mirror in a semi-confocal Fabry-Perot (FP) cavity, as illustrated in FIG. **5**A and FIG. **5**B. Results of mirror position scans reveal cavity mode structures and positions (see FIG. **6**) for a given transmission (Tx) frequency. Alignment of the circuit board normal to the positioner axis dramatically improves the symmetry and quality factors of observable modes. The higher order modes, which have a wider spatial footprint as they radiate off the coupler, are observed to decrease in magnitude more rapidly than the primary (nodeless) TEM00 mode, which has the highest quality factor for a given mode number. The mode number is the number of wavelengths spanning the round-trip cavity distance for a given mirror position. The decrease in quality factor with mode order (TEMnm, n,m>0) is an indicator of the domination of diffractive losses in this system. Tests with larger diameter mirrors indicate a significant increase in the mode structure that can lead to interferences at specific frequencies. Positioning of the stage with respect to detected modes is highly reproducible and modes are easily tracked in frequency space with mirror position adjustments.

[0071] A suitable driving signal for Tx and Rx is chosen, usually with a fixed intermediate frequency (IF) and the two may then be scanned to determine the frequency response of the system. For small scans (<100 MHz, or within a primary mode) the oscillators inside the chips remain locked over the scan range. In one or more examples, scanning across the full bandwidth (see FIG. **7**) is achieved by periodic re-locking of the oscillators through the command interface. The same primary, secondary, and tertiary mode structures are observed in frequency and position scanning. The modes shift under vacuum conditions due primarily to the change in refractive index of the medium.

[0072] FIG. **9** illustrates a signal obtained using the spectrometer including the coupler when the cavity contains CH_3CN molecules interacting with the electromagnetic radiation inputted into the cavity through the waveguide **110** in the coupler **100**. The signal is derived from the output electric field received in the receiver from the waveguide **110** in the coupler **100**.

[0073] Process Steps

[0074] FIG. **10** is a flowchart illustrating a method of making a coupler for coupling electromagnetic radiation having a wavelength λ (e.g. , at band center) into a cavity, according to one or more embodiments (referring also to FIGS. **1**A-**1**D, **2**, **4**, and **5**A-**5**C.

[0075] Block **1000** represents providing a mirror **102** including a metal layer **104** having a reflective surface **106** on a substrate. The metal layer **104** includes a ground plane **108**. A main ground plane is formed on a backside of the substrate.

[0076] Block **1002** represents patterning one or more waveguides **110** for gigahertz or terahertz electromagnetic radiation so that each of the waveguides are embedded in the metal layer **104** and include (1) two openings **114** in the metal layer **104** exposing a dielectric **112** under the metal layer **104**; and (2) a section **116** of the metal layer **104** between the two openings. The patterning further comprises patterning a plurality of holes **118** in the metal layer **104** disposed along an edge of the openings **114**, the holes exposing the dielectric under the metal layer.

[0077] Block **1004** represents the end result, a coupler **100**. The coupler can be embodied in many ways including, but not limited to the following.

[0078] 1. The coupler wherein the holes **118** are disposed around a perimeter of the waveguide **110**.

[0079] 2. The coupler wherein the holes **118** are disposed in a hexagonal pattern.

[0080] 3. The coupler of one or any combination of the previous examples wherein the holes have a diameter D or a width in a range of λ/15-λ/5 or 200-600 micrometers.

[0081] 4. The coupler of one or any combination of the previous examples wherein the holes **118** are separated by a distance in a range of λ/5-λ/2 or 600-1500 micrometers (distance from a center of one hole to a center of an adjacent hole)

[0082] 5. The coupler of one or any combination of the previous examples wherein the holes **118** are disposed in 2-4 rows.

[0083] 6. The coupler of one or any combination of the previous examples, wherein the openings **114** in the waveguide **110** have a width W**1** in a range of λ/5-λ/2, where λ is the wavelength at band center, or 600-1500 micrometers.

[0084] 7. The coupler of one or any combination of the previous examples, wherein the openings each have an L shape having a base portion **124** and a back portion **126**.

[0085] 8. The coupler of example 7, wherein the base portion **124** has a length L**5** in a range of λ/2-4 λ, or 1-4 mm and the back portion **126** has a length L**1** in a range of 3 λ-15 λ, or 5-15 mm.

[0086] 9. The coupler of example 7 or 8, wherein the L shapes are positioned symmetrically about the section **116** of the metal layer **104** so as to form mirror images of each other with respect to the section **116** of the metal layer **104**.

[0087] 10. The coupler of one or any combination of the previous examples, further comprising two of the waveguides **110** embedded in the metal layer **104**, wherein each waveguide **110***a* is a mirror image of the other waveguide **110***b* about an axis of symmetry **128** of the metal layer **104**.

[0088] 11. The coupler of example 10, wherein the openings **114** each have an L shape having a base portion **124** and a back portion **126**; the L shapes in each waveguide **110***a*, **110***b* are positioned symmetrically about the section **116** of the metal layer **104** so as to form mirror images of each other with respect to the section of the metal layer **104**, and a perpendicular distance **130** between the base portions **124**, in one of the waveguides **110***a*, to the base portions **124** in the other waveguide **110***b* in the pair, is in a range of λ/2-3 λ or 2-10 mm.

[0089] 12. The coupler of example 11, wherein the reflective surface is rectangular and has sides having a length **134** in a range of 3 λ-15 λ, or 10-50 mm.

[0090] 13. The coupler of example 11, wherein the reflective surface is rectangular and has a first side opposite a second side, the first side and the second side each having a length in a range of 3 λ-15 λ, or 10-50 mm; the waveguides include a first waveguide and a second waveguide, the openings and the section in the first waveguide extend to the first side, and the openings and the section in the second waveguide extend to the second side.

[0091] 14. The coupler of one or any combination of the previous examples, wherein the waveguides **110** each comprise a stripline including the section of metal between two sections of the ground plane **108**.

[0092] Block **1006** represents optionally coupling the coupler **100** to a second mirror **200** so as to form a cavity **202** confining the electromagnetic radiation and generating modes of the electromagnetic radiation in the cavity when the electromagnetic radiation is coupled into the cavity through the coupler. The modes comprise peaks **400** and nodes of a cavity electric field evenly spaced along the cavity's longitudinal axis (cavity axis), and the cavity electric field is symmetrically distributed in at least one direction perpendicular to the cavity axis. In one example, the cavity electric field at a first point P**1** and a second point P**2** symmetrically positioned on either side of the cavity's axis are the same to within 10%. In one or more further examples, the first point and the second point are each at a same distance in a range of λ-3 λ or 3-10 mm, from the axis.

[0093] The coupler **100** is comprised of a slot **124**, **124***a* (the short legs of the "Ls") that radiates the signal (e.g., as electromagnetic radiation **204** into the semi-confocal resonator **202**. The slot **126***a* radiates due to an electric field across the slot that is excited by a short "stub" antenna that receives the signal from the transmitter **502** along a coplanar waveguide (CPW) transmission line (the two parallel long legs **126***a*, **126** of the "L"s). The cluster of via holes **118** confines the signal to the CPW line and the slot, preventing it from leaking into the dielectric **112** region under the top ground plane **108**. The second slot **124***b* works in reverse to convey the resonator signals to the receiver **504**.

[0094] The coupler **100** radiates only weakly into the resonator **202**, requiring several hundred cycles of the signal to build up the electric field in the resonator to its peak value. This is required to enable the resonator to have the high quality factor necessary for operation: the reciprocity principle of electromagnetism dictates that a more efficient radiator would also allow the signal to leak prematurely back into the CPW lines to the transmitter and receiver.

[0095] Block **1008** represents providing an apparatus (e.g., spectrometer **500**, amplifier, or filter) including the coupler of one or any combination of the examples described above. The spectrometer/apparatus includes a transmitter **502** coupled to the coupler **100**, wherein the transmitter transmits an electric field to the coupler and the electric field is transmitted along the waveguide and generates the electromagnetic radiation outputted from the coupler into the cavity. The spectrometer/apparatus further includes a receiver **504** coupled to the coupler for receiving an output electric field transmitted along the waveguide in response to a presence of a molecule in the cavity interacting with the cavity electrical field of the electromagnetic radiation. A computer coupled to the receiver determines a composition of the molecule from the output electric field.

[0096] In one or more examples, the transmitter includes a first output electrically connected to the center section of the waveguide at a side of the metal layer; and a second output electrically connected to the ground plane at the side of the metal layer so as to apply an electrical field across the section and the ground plane. The spectrometer further includes a receiver including a first input electrically connected to the section of the waveguide at the side of the metal layer, and a second input electrically connected to the ground plane so as to receive the output electrical field applied across the section of the waveguide and the ground plane in response to the molecule in the cavity interacting with the cavity electrical field.

[0097] Advantages and Improvements

[0098] Previous attempts to utilize mm-wave cavities for pulsed detection schemes have largely been stymied due to difficulties with coupling radiation efficiently into high finesse cavities. Some exploratory studies using wire-polarizer-based coupling schemes have been described [13,14] but power limitations and system inefficiencies precluded molecular detections. Some success has been documented employing a technique used in cm-wave experiments where radiation is waveguide-coupled into the cavity through an aperture in a spherical end mirror. This approach has reported sensitive detections at 88 GHz [16] however, it requires large optical components and the waveguide feeds limit the application to frequencies <90 GHz. Other success has also been documented [17] at140 GHz where radiation was injected into an optical cavity via the waveguide attached to an end mirror outfitted with electro-formed coupling holes. Finally, cavity ringdown absorption spectroscopy has shown some promise at 94 GHz. [9]. In this example, the resonator mode-width was narrower than the targeted absorption feature; thus, only broadband attenuation rather than direct rotational lines were observed. The motif common to all these approaches is that the radiation generated from bulky traditional mm-wave sources (e.g., klystron, backward-wave oscillator, and GaAs-based multiplier chain) is injected into the optical cavity through an end mirror element.

[0099] By contrast, the spectrometer described herein includes a coupler plate that (1) serves as an end mirror and (2) also hosts waveguide features for the direct injection (detection) of radiation into (out of) the optical cavity. This fundamentally different approach mitigates the loss issues that have plagued some other mm-wave cavity systems while maintaining a compact planar system geometry. A surprising and unexpected feature of the coupler was its relatively high Q factors (narrow linewidths)

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CONCLUSION

[0117] This concludes the description of the preferred embodiment of the present invention. The foregoing description of one or more embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

What is claimed is:

1. A coupler for coupling electromagnetic radiation having a wavelength λ into a cavity, comprising:
- a mirror including a metal layer having a reflective surface, the metal layer forming a ground plane;
- one or more waveguides for gigahertz or terahertz electromagnetic radiation, each of the waveguides embedded in the metal layer and including:
  - two openings in the metal layer exposing a dielectric under the metal layer; and
  - a section of the metal layer between the two openings; and
- a plurality of holes in the metal layer disposed along an edge of the openings, the holes exposing the dielectric under the metal layer.

2. The coupler of claim **1**, wherein the holes are disposed around a perimeter of the waveguide.

3. The coupler of claim **2**, wherein the holes are disposed in a hexagonal pattern.

4. The coupler of claim **2**, wherein the holes have a diameter or a width in a range of λ/15-λ5 or 200-600 micrometers.

5. The coupler of claim **2**, wherein the holes are separated by a distance in a range of λ/5-λ/2 or 600-1500 micrometers (distance from a center of one hole to a center of an adjacent hole).

6. The coupler of claim **2**, wherein the holes are disposed in 2, 3, or 4 rows.

7. The coupler of claim **1**, wherein the openings have a width in a range of λ/5-λ/2.

8. The coupler of claim **1**, wherein the openings each have an L shape having a base portion and a back portion.

9. The coupler of claim **8**, wherein the base portion has a length in a range of λ/2-4 λ or 1-4 mm and the back portion has a length in a range of 3 λ-15 λ or 5-15 mm.

10. The coupler of claim **2**, wherein the L shapes are positioned symmetrically about the section of the metal layer so as to form mirror images of each other with respect to the section of the metal layer.

11. The coupler of claim **1**, further comprising two of the waveguides embedded in the metal layer, wherein each waveguide is a mirror image of the other waveguide about an axis of symmetry of the metal layer.

12. The coupler of claim **11**, wherein:

the openings each have an L shape having a base portion and a back portion.

the L shapes in each waveguide are positioned symmetrically about the section of the metal layer so as to form mirror images of each other with respect to the section of the metal layer, and

a perpendicular distance between the base portions, in one of the waveguides, to the base portions in the other waveguide, is in a range of λ/2-3 λ.

13. The coupler of claim **12**, wherein the reflective surface is rectangular and has sides having a length in a range of 3 λ-15 λ.

14. The coupler of claim **12**, wherein:

the reflective surface is rectangular and has a first side opposite a second side, the first side and the second side each having a length in a range of 3 λ-15 λ,

the waveguides include a first waveguide and a second waveguide,

the openings and the section in the first waveguide extend to the first side, and

the openings and the section in the second waveguide extend to the second side.

15. The coupler of claim **1**, wherein the waveguides each comprise a stripline including the section of metal between two sections of the ground plane.

16. The coupler of claim **1**, wherein:

the coupler coupled to a second mirror forms a cavity confining the electromagnetic radiation and generating modes of the electromagnetic radiation in the cavity when the electromagnetic radiation is coupled into the cavity through the coupler,

the modes comprise peaks and nodes of a cavity electric field evenly spaced along the cavity's longitudinal axis (cavity axis), and

the cavity electric field is symmetrically distributed in at least one direction perpendicular to the cavity axis.

17. The coupler of claim **1**, wherein:

the coupler coupled to a second mirror forms a cavity confining the electromagnetic radiation and generating modes of the electromagnetic radiation in the cavity when the electromagnetic radiation is coupled into the cavity through the coupler,

the modes comprise peaks and nodes of a cavity electric field spaced along the cavity's longitudinal axis (cavity axis),

the cavity electric field at a first point and a second point symmetrically positioned on either side of the cavity's axis are the same to within 10%.

18. The coupler of claim **17**, wherein the first point and the second point are each at a same distance in a range of λ-3 λ from the axis.

19. A spectrometer comprising the cavity of claim **12**, comprising:

a transmitter coupled to the waveguide, wherein the transmitter transmits an electric field to the waveguide, wherein the electric field is transmitted along the waveguide and generates the electromagnetic radiation outputted from the coupler into the cavity;

a receiver coupled to the waveguide, the waveguide receiving an output electric field transmitted along the waveguide in response to a presence of a molecule in the cavity and interacting with the cavity electrical field of the electromagnetic radiation; and

a computer coupled to the receiver determining a composition of the molecule from the output electric field.

20. The spectrometer of claim **19**, wherein:

the openings and the section in the first waveguide extend to a side of the reflective surface, further comprising:

the transmitter including:

a first output electrically connected to the section at the side; and

a second output electrically connected to the ground plane at the side; and

wherein the first and second outputs apply an electrical field across the section and the ground plane; and

a receiver including:

a first input electrically connected to the section at the side; and

a second input electrically connected to the ground plane

wherein the first and second inputs receive the output electrical field applied across the section and the ground plane in response to the molecule in the cavity interacting with the cavity electrical field.

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