(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
5 March 2009 (05.03.2009)

PCT

(10) International Publication Number
WO 2009/029282 Al

(51) International Patent Classification:
G02B 6/26 (2006.01)

(21) International Application Number:
PCT/US2008/0 10289

(22) International Filing Date: 29 August 2008 (29.08.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/967,168 31 August 2007 (3 1.08.2007) US

(71) Applicant *(for all designated States except US):* ET IN¬DUSTRIES, INC. [US/US]; 50 Intervale Road, Boonton, NI 07005 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only):* HOWARD, John [US/US]; 64 Alexandra Circle, Upper Mount Bethel, PA 18343 (US).

(74) Agent: TURNER, Rod, S.; Hoffmann & Baron, LLP, 6900 Iericho Turnpike, Syosset, NY 11791 (US).

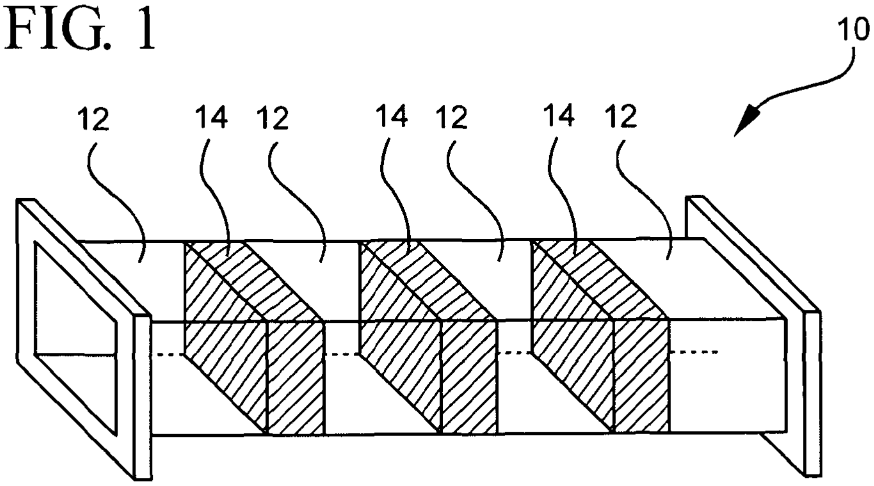
(81) Designated States *(unless otherwise indicated, for every kind of national protection available):* AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, IP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available):* ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(54) Title: TM MODE EVANESCENT WAVEGUIDE FILTER

FIG. 1



(57) Abstract: Waveguide filters utilizing the TM modes in an evanescent waveguide are provided. The Q of such filters surpasses any evanescent, dual and triple mode filters in propagating or evanescent waveguides. The waveguide filter in accordance with the present invention features a small size, as well as ease and simplicity in its manufacture when compared with conventional filters. Filters of exceptionally high Q and very low loss, when compared to conventional filters, can be obtained by employing TM modes in an evanescent waveguide. The TM mode evanescent filter has a higher Q than either the evanescent TE mode standard filter of a single mode propagating waveguide (TM or TE) or even the dual or triple mode filters in evanescent or propagating waveguides.

WO 2009/029282 A1

TM MODE EVANESCENT WAVEGUIDE FILTER

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority based on U.S. Provisional Application Serial No. 60/967,168 filed on August 31, 2007, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention generally relates to waveguide filters, and more particularly to utilizing electric (E) field or TM modes in evanescent waveguides.

Brief Discussion of the Related Art

[0003] Radio transmitters and receivers require filters to remove or suppress unwanted frequencies from being transmitting or received. The transmitter portion of a radio may generate frequencies that will interfere with the radio system, or that may be prohibited by a radio frequency spectrum governing body. The receiver may need to suppress unwanted signals at different frequencies generated by the transmitter, or received from an external source, which would adversely affect the performance of the receiver.

[0004] At millimeter- wave frequencies sources of unwanted frequencies include the local oscillator frequency, image frequencies from the mixer, and the transmitter frequencies (in the case of the receiver). The frequencies generated by the mixer and the local oscillator are functions of the selected radio architecture. The closer the oscillator frequency (or its harmonics) is to the transmitter frequencies, the more difficult it is to remove the undesired frequency. However, wider spaced frequencies may result in more complex circuitry resulting in a more expensive radio implementation. A small separation between the transmit and receive frequencies can result in unwanted high power transmit frequencies leaking into the receiver. The separation between the transmit and receive frequencies is usually specified by the licensing bodies and the system operators. The radio designer may not have control over this specification.

[0005] To suppress unwanted frequencies below an acceptable power level, a filter element is required in the signal path. The filter element discriminates between the desired and undesired frequencies based on the wavelengths of the signals. At millimeter-wave frequencies the difference between the wavelengths is very small, resulting in very high manufacturing tolerances.

SUMMARY OF THE INVENTION

[0006] In conventional waveguide filters, the dominant HlO mode is usually present. The electric field modes, or TM modes, are usually avoided since designs using TM modes become more cumbersome and the filters become less stable or reliable without any apparent advantage. However, in below cutoff waveguides, utilization of the electric (E) field advantageously introduces very high Q's in very small and thus lightweight filters.

[0007] The present invention relates to waveguide filters utilizing the TM modes in an evanescent waveguide. The Q of such filters surpasses any evanescent, dual and triple mode filters in propagating or evanescent waveguides. The waveguide filter in accordance with the present invention features a small size, as well as ease and simplicity in its manufacture when compared with the above-mentioned conventional filters.

[0008] Filters of exceptionally high Q and very low loss, when compared to all other filters in existence today, can be obtained by employing TM modes in an evanescent waveguide. The TM mode evanescent filter has a higher Q than either the evanescent TE mode standard filter of a single mode propagating waveguide (TM or TE) or even the dual or triple mode filters in evanescent or propagating waveguides.

[0009] In accordance with one aspect of the present invention, a waveguide filter is provided which includes at least one evanescent waveguide section, and at least one propagating dielectric filled waveguide section coupled to the at least one evanescent waveguide section. The waveguide filter utilizes at least one TM mode.

[0010] The at least one evanescent waveguide section may be defined using the following equations:

$$Y_{e|i} = -\frac{1}{jX_0}\coth \gamma l_{e|i} \tag{1}$$

$$\sinh\left(\gamma_e l_{e|i}\right) = -\frac{\Delta\omega_0}{\omega_2-\omega_1}\sqrt{\frac{g_i g_{i+1}}{\omega_0 C_i \omega_0 C_{i+1}}} \tag{2}$$

$$\omega_0 C_1 = \coth \gamma_e l_{e|i-1} + \coth \gamma l_{e|i} = Y_{e|i-1} + Y_{e|i} \quad \text{normalized} \tag{3}$$

where $Y_{e|i}$ is a resultant admittance of a capacitor associated with a J inverter in the evanescent waveguide, l_e is a length of the evanescent sections, γ_e is a propagation constant inside the evanescent waveguide, ω_0 is associated with a center frequency of the filter, ω_1 and ω_2 are associated with a lower and upper passband edges, respectively, g_i are low-pass prototype values, and Δ is a correction factor for the TM modes, which corrects the steeper frequency response of the evanescent cut-off compared to lumped elements and is given by:

$$\Delta = \frac{2}{1+\frac{1}{1-\left(\frac{\lambda_c}{\lambda_0}\right)^2}} \tag{4}$$

where λ_c is a cutoff wavelength and λo is a wavelength at the center frequency.

[001 1] The the at least one propagating dielectric filled waveguide section may be defined using the following equations:

$$\beta_p l_{p|\iota} = \pi - \varphi_\iota - \varphi_{\iota+1} \tag{5}$$

$$\varphi_\iota = \tan^{-1}\left(\frac{Z_{0|e}}{jZ_{0|p}} \cdot \tanh\left(\gamma_e l_{e|\iota}\right)\right) \tag{6}$$

where β_p is a propagation constant in the propagating dielectric-filled waveguide, l_p is a length of each propagating section, $Zo\backslash_e$ is a characteristic impedance of the evanescent waveguide, which is imaginary in nature, Zo_p is a characteristic impedance of the propagating dielectric-filled waveguide, which is real in nature, and ϕ, is a phase associated with the admittance $Y_{e\backslash'}$.

[0012] Other objects and features of the present invention will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed as an illustration only and not as a definition of the limits of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Figure 1 shows the structure of an evanescent waveguide filter utilizing dielectric sections in accordance with the present invention.

[0014] Figure 2A shows an evanescent waveguide section in the TM field modeled as a FI network.

[00 15] Figure 2B shows an evanescent waveguide section in the TM field modeled as a T network.

[0016] Figure 3 shows a model of the waveguide filter in accordance with the present invention employing the II network of Figure 2A. An equivalent model using the FI network with J-invertors is shown in Figure 4.

[0017] Figure 4 shows a model of the waveguide filter in accordance with the present invention employing the Fl network of Figure 2A with J-inverters.

[0018] Figure 5A shows the Q factor of an evanescent waveguide operating in the TE mode.

[0019] Figure 5B shows the Q factor of an evanescent waveguide operating in the TM mode.

[0020] Figures 6A and 6B show a comparison in frequency responses between TE and TM evanescent waveguide filter structures.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] A waveguide filter 10 formed in accordance with the present invention is shown in Figure 1. The waveguide filter 10 includes at least one evanescent waveguide section 12 and at least one propagating dielectric filled waveguide section 14coupled to the at least one evanescent waveguide section. The waveguide filter utilizes at least one TM mode.

[0022] In conventional waveguide filters, the dominant HlO mode is usually present. The electric field modes, or TM modes, are usually avoided since designs using TM modes become more cumbersome and the filters become less stable or reliable without any apparent advantage. However, in below cutoff waveguides, utilization of the electric (E) field advantageously introduces very high Q's in very small and thus lightweight filters.

[0023] The present invention relates to waveguide filters utilizing the TM modes in an evanescent waveguide. The Q of such filters surpasses any evanescent, dual and triple mode filters in propagating or evanescent waveguides. The waveguide filter in accordance with the present invention features a small size, as well as ease and simplicity in its manufacture when compared with the above-mentioned conventional filters.

[0024] Filters of exceptionally high Q and very low loss, when compared to all other filters in existence today, can be obtained by employing TM modes in an evanescent waveguide. The TM mode evanescent filter has a higher Q than either the evanescent TE mode standard filter of a single mode propagating waveguide (TM or TE) or even the dual or triple mode filters in evanescent or propagating waveguides. Figures 5A and 5B show a comparison of the Q of waveguides below and above cutoff for the TE and TM modes.

[0025] Evanescent TM waveguide filters can be analyzed using transmission line theory. Figures 5A and 5B provide a theoretical comparison between the TE evanescent waveguide filter as described in further detail in G. F. Craven and C. K. Mok, "The Design of Evanescent Mode Waveguide Bandpass Filters for a Prescribed Insertion Loss Characteristic", IEEE Transactions on Microwave Theory and Techniques, Vol. MTT- 19, No. 3, March 1971; Dr. John Howard and Wenny Lin, "Evanescent Mode Filter: Design and Implementation" Microwave Journal, Oct 1989; and Dr. J. Howard and M. Lavey, "Simplified method eases the design of bandpass filters", Microwaves and RF, Dec 2000, which are incorporated herein by reference. The TM evanescent waveguide filter presented on this invention, for a very narrow bandwidth of 0.1%. As seen from the analysis the Q of the TM mode evanescent filter is greater than the Q of the TE mode evanescent filter.

[0026] The design of the TM evanescent waveguide filter in accordance with the present invention will now be discussed. An evanescent waveguide section in the TM field can be modeled as a FI network as shown in Figure 2A, or a T network as shown in Figure 2B.

[0027] Employing the π network of Figure 2A, sections of high Q dielectric, are added in order to form the filter shown in Figure 3. This process is described in further detail in N. McN. Alford, S.J. Penn, A. Templeton, X. Wang, J.C.

Gallop, N. Klein, C. Zuccaro and P. Filhol, "Microwave Dielectrics", IEEE Colloquium on Electro-technical Ceramics - Processing, Properties and Applications (Ref. No: 1997/317), Nov 1997, which is incorporated herein by reference. An equivalent model using the π network with J-invertors for more straightforward calculations is shown in Figure 4.

[0028] The equations associated with the above structure are as follows:

$$Y_{e|i} = -\frac{1}{jX_0}\coth \gamma_e l_{e|i} \tag{1}$$

$$\sinh\left(\gamma_e l_{e|i}\right) = -\frac{\Delta\omega_0}{\omega_2 - \omega_1}\sqrt{\frac{g_i g_{i+1}}{\omega_0 C_i \omega_0 C_{i+1}}} \tag{2}$$

$$\omega_0 C_i = \coth \gamma_e l_{e|i-1} + \coth \gamma_e l_{e|i} = Y_{e|i-1} + Y_{e|i} \quad \text{normalized} \tag{3}$$

where $Y_{e|i}$ is the resultant admittance of the capacitor associated with the J inverter in the evanescent waveguide, l_e is the length of the evanescent sections, y_e is the propagation constant inside the evanescent waveguide, ω_0 is associated with the center frequency of the filter, ω_1 and ω_2 are associated with the lower and upper passband edges, respectively, g_i are the low pass prototype values, and Δ is the correction factor for the TM modes, which corrects the steeper frequency response of the evanescent cut-off compared to lumped elements and is given by:

$$\Delta = \frac{2}{1 + \frac{1}{1 - \left(\frac{\lambda_c}{\lambda_0}\right)^2}} \tag{4}$$

where λ_c is the cutoff wavelength and λ_0 the wavelength at the center frequency.

In between the evanescent sections, there are propagating dielectric filled waveguide sections. The equations associated with the resonance of the propagating sections are as follows:

$$\beta_p l_{p|i} = \pi - \varphi_i - \varphi_{i+1} \qquad (5)$$

$$\varphi_i = \tan^{-1}\left(\frac{Z_{0|e}}{jZ_{0|p}} \cdot \tanh\left(\gamma_e l_{e|i}\right)\right) \qquad (6)$$

where β_p is the propagation constant in the propagating dielectric-filled waveguide and l_p is the length of each propagating section, $Z_{0|e}$ is the characteristic impedance of the evanescent waveguide, which is imaginary in nature, $Z_{0|p}$ is the characteristic impedance of the propagating dielectric-filled waveguide ,which is real in nature, and ϕ_i is the phase associated with the admittance $Y_{e|i}$.

[0029] An example will now be discussed. To design a bandpass Chebyshev filter with a passband between 3.998 and 4.002 GHz, a ripple of 0.1dB, a stopband between 3.09 and 4.01, and an attenuation of 100dB, the corresponding low-pass prototype values are as follows:

g_0=1;
g_1=0.7970;
g_2=1.3924;
g_3=1.7481;
g_4=1.6331;
g_5=1.7481;
g_6=1.3924;
g_7=0.7970; and
g_8=1.

[0030] The selected waveguide is WR90 with internal dimensions of 0.9in by 0.4in. The dielectric chosen is $Ba(Mg_{1/3}Ta_{2/3})O_3$. Although this dielectric material does not have the highest Q, its dielectric constant of 24 suits this design. The Q of this material is 65,000 at 4GHz, as described in further detail in N. McN. Alford, S.J. Penn, A. Templeton, X. Wang; J.C. Gallop, N. Klein, C.

Zuccaro and P. Filhol, "Microwave Dielectrics", IEEE Colloquium on Electro-technical Ceramics Processing, Properties and Applications (Ref. No: 1997/317), Nov 1997. The Q of the evanescent waveguide at 4 GHz is over 176,000, which is shown in Figure 5B.

[0031] Using the above lowpass prototype values and by iterating equations (1) to (3) above, the evanescent lengths are found as follows:

l_0= 1.181 1;
l_1= 0.8320;
l_2= 0.8791;
l_3= 0.8887;
Ir= 0.8887;
l_5= 0.8791;
Ie= 0.8320; and
l_7= 1.181 1.

[0032] The first and last lengths are arbitrary, but long enough to provide the desired attenuation. The propagating lengths in the dielectric are calculated using equations (5) and (6) as follows:

l_{p0}= 1.0141;
l_{p1}= 1.0141;
l_{p2}= 1.0141;
l_{p3}= 1.0141;
l_{p4}= 1.0141;
l_{p5}= 1.0141; and
l_{p6}= 1.0141.

[0033] The performance of this filter is shown by curve A in Figures 6A and 6B and compared with a standard evanescent waveguide filter (TE mode) shown by curve B. Figure 6b is an exploded view of the lower portion of Figure 6A.

[0034] Although the example refers to a bandpass filter in a rectangular waveguide, it is also intended to be within the scope of the present invention to be able to implement highpass, lowpass, and bandstop filters with various crosssectional shapes, such as, but not limited to circular, square and other shapes known in the art using the equations defined above.

[0035] Although illustrative embodiments of the present invention have been described herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to those precise embodiments, and that various other changes and modifications may be affected therein by one skilled in the art without departing from the scope or spirit of the invention.

What is claimed is:

1. A waveguide filter comprising:

at least one evanescent waveguide section; and

at least one propagating dielectric filled waveguide section coupled to the at least one evanescent waveguide section, the waveguide filter utilizing at least one TM mode.

2. The waveguide filter defined by Claim 1, wherein the at least one evanescent waveguide section is defined using the following equations:

$$\gamma_{e|} = -\frac{1}{jXo} \coth \gamma j_{e|} \qquad (1)$$

$$\sinh\left(\gamma_e l_{e|}\right) = -\frac{\Delta\omega_0}{\omega_2 - \omega_1}\sqrt{\frac{g_i g_{i+1}}{\omega_0 C_i \omega_0 C_{i+1}}} \qquad (2)$$

$$\omega_0 C_1 = \coth \gamma_e l_{e,l-1} + \coth \chi j_{e|l} = Y_{e|,-} + 7_{e|}, \quad \text{normalized} \qquad (3)$$

where $Y_{e|}$ is a resultant admittance of a capacitor associated with a J inverter in the evanescent waveguide, l_e is a length of the evanescent sections, γ_e is a propagation constant inside the evanescent waveguide, ωo is associated with a center frequency of the filter, $ɯ_l$ and $a >_2$ are associated with a lower and upper passband edges, respectively, g, are low-pass prototype values, and Δ is a correction factor for the TM modes, which corrects the steeper frequency response of the evanescent cut-off compared to lumped elements and is given by:

$$\Delta = \frac{2}{1 + \frac{1}{1 - \left(\frac{\lambda_c}{\lambda_0}\right)^2}} \qquad (4)$$

where λ_c is a cutoff wavelength and λo is a wavelength at the center frequency.

3. The waveguide filter defined by Claim 1, wherein the at least one propagating dielectric filled waveguide section is defined using the following equations:

$$\beta_p l_{p|i} = \pi - \varphi_i - \varphi_{i+1} \quad (5)$$

$$\varphi_i = \tan^{-1}\left(\frac{Z_{0|e}}{jZ_{0|p}} \cdot \tanh\left(\gamma_e l_{e|i}\right)\right) \quad (6)$$

where β_p is a propagation constant in the propagating dielectric-filled waveguide, l_p is a length of each propagating section, $Zo_{\backslash e}$ is a characteristic impedance of the evanescent waveguide, which is imaginary in nature, $zo\backslash_p$ is a characteristic impedance of the propagating dielectric-filled waveguide, which is real in nature, and ϕ, is a phase associated with the admittance $Y_{e}\backslash$.

FIG. 1

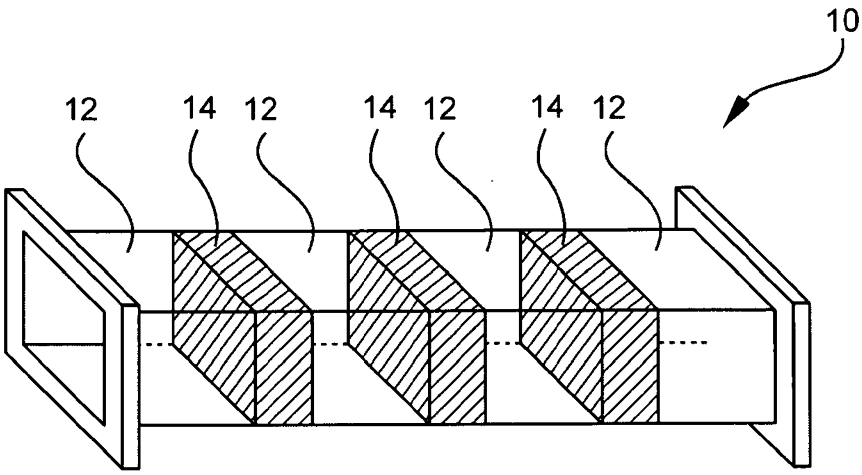


FIG. 2A

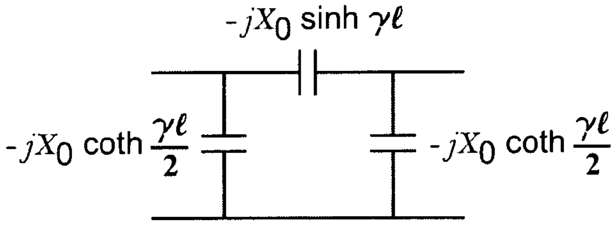


FIG. 2B

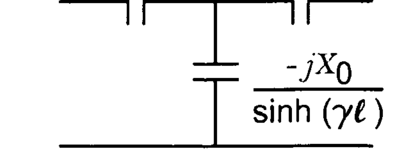


FIG. 3

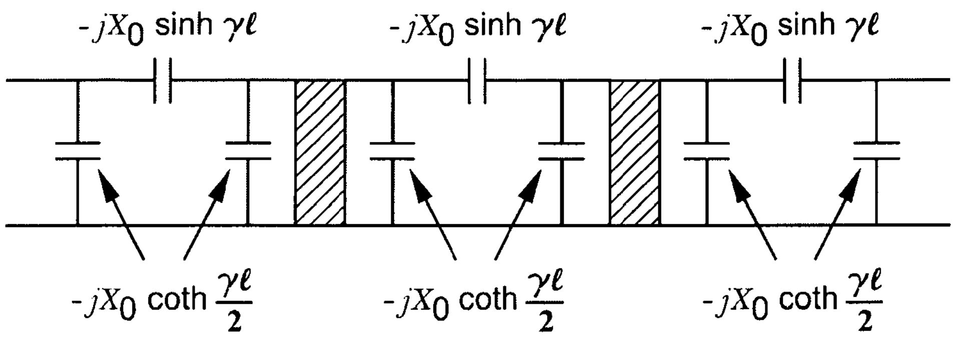

-jX0 sinh γℓ
-jX0 sinh γℓ
-jX0 sinh γℓ
-jX0 coth γℓ/2
-jX0 coth γℓ/2
-jX0 coth γℓ/2

FIG. 4

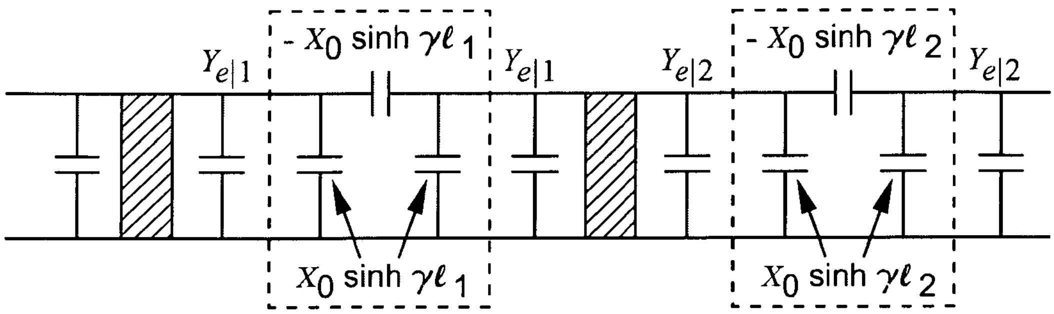

Ye|1
- X0 sinh γℓ1
Ye|1
Ye|2
- X0 sinh γℓ2
Ye|2
X0 sinh γℓ1
X0 sinh γℓ2

FIG. 5A

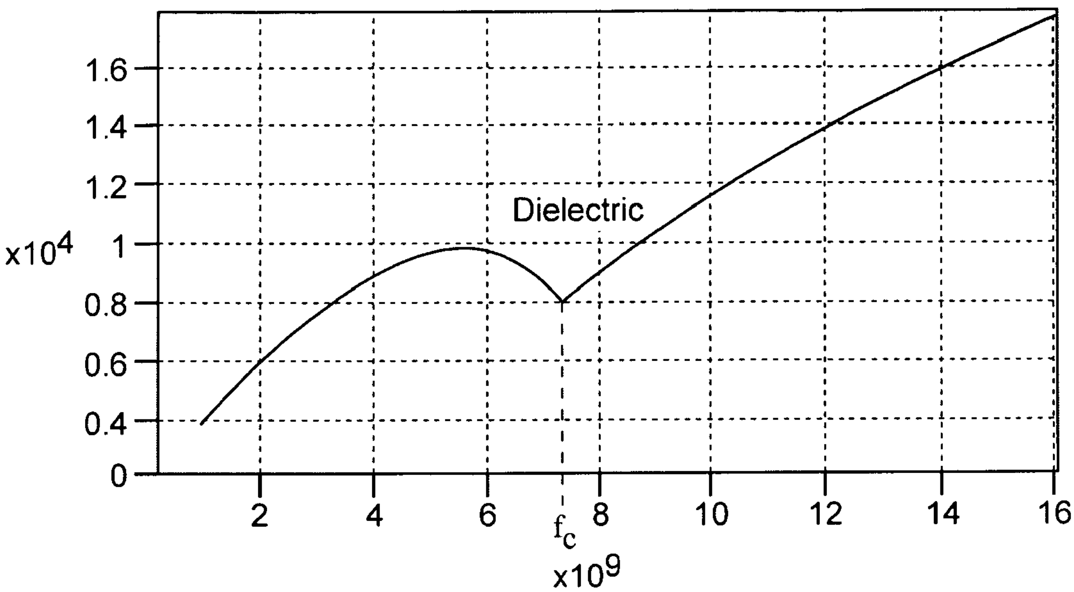

1.6
1.4
1.2
x10^4
1
0.8
0.6
0.4
0
Dielectric
2
4
6
fc
8
10
12
14
16
x10^9

FIG. 5B

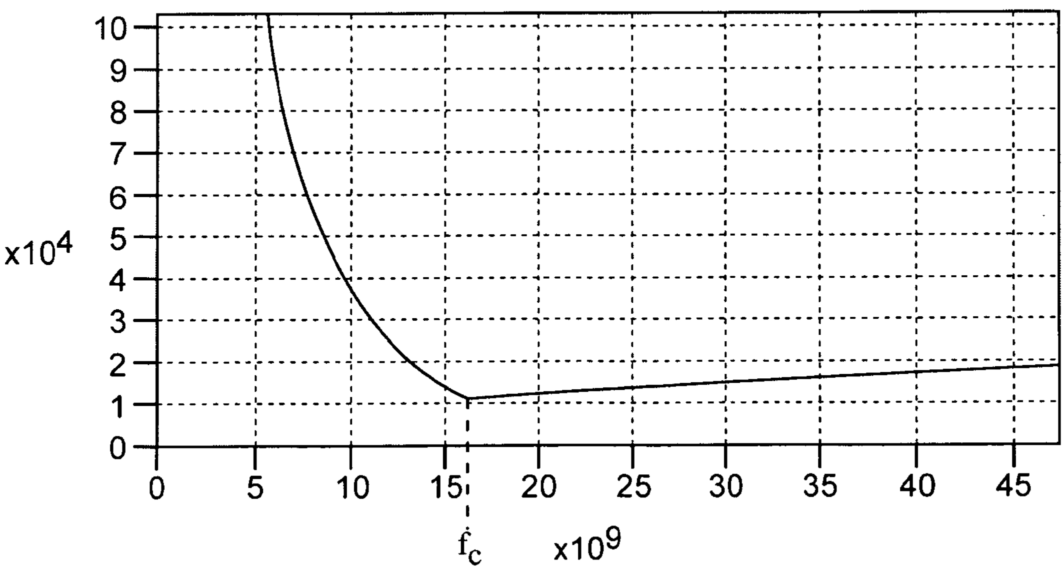

10
9
8
7
6
5
x10^4
4
3
2
1
0
0
5
10
15
fc
20
25
30
35
40
45
x10^9

FIG. 6A

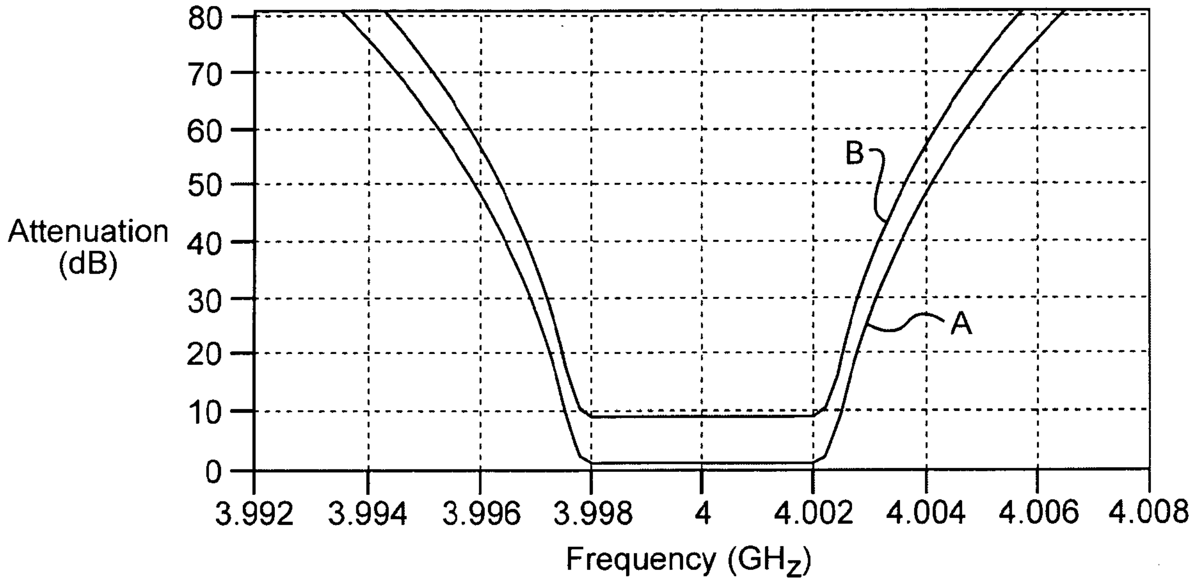
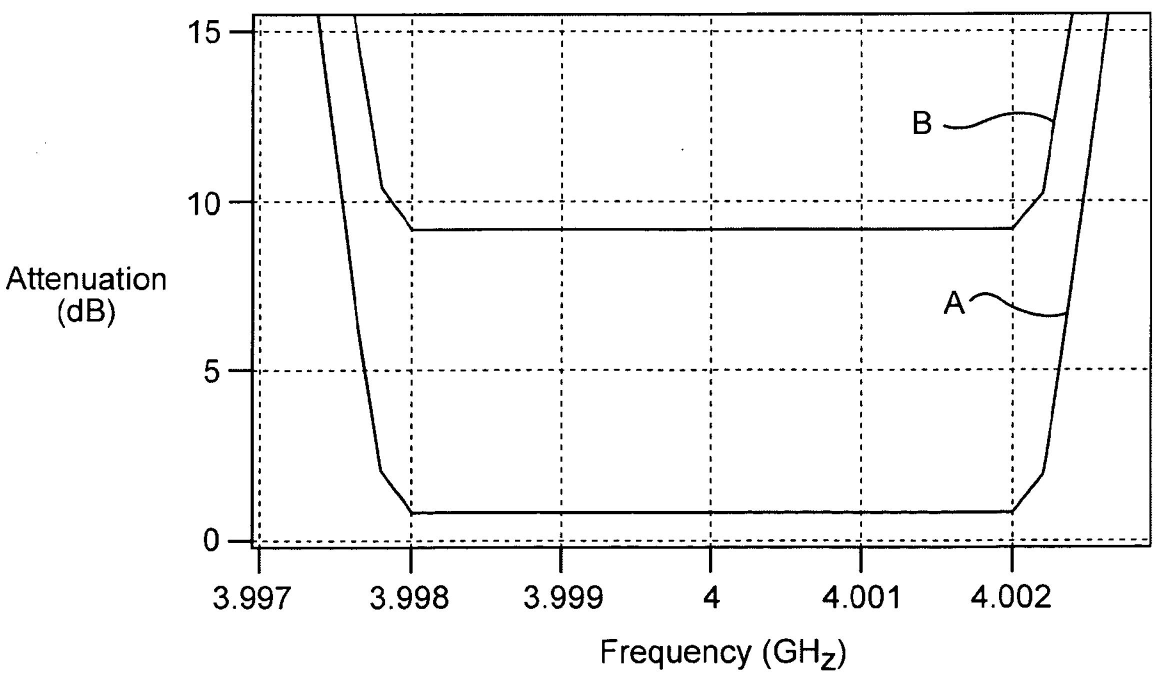

80
70
60
50
40
30
20
10
0
Attenuation (dB)
B
A
3.992
3.994
3.996
3.998
4
4.002
4.004
4.006
4.008
Frequency (GHz)

FIG. 6B


15
10
5
0
Attenuation (dB)
B
A
3.997
3.998
3.999
4
4.001
4.002
Frequency (GHz)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/1Q289

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G02B 6/26 (2008.04)
USPC - 385/30
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC - 385/30

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 385/30, 385/39; 385/52; 359/885

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Dialog Classic (Chinese Patent Abstracts in English, Derwent World Patents Index, European Patents Full Text, French Patents, Japanese Patent Abstracts in English, U.S. Patents Full Text/1976 to present, WIPO/PCT Patents Full Text), Google Scholar; Terms searched: coth, cotangent, cut-off, dielectπc, evanescent...

C DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BLONDY, P.; BALERAS, F.; CROS, D.; MASSIT, C ; ZANCHI, C ; LAPIERRE, L.; and SOMBRIN, J. Integrated Millimeter-Wave Silicon Micromachined Filters. European Microwave Conference, 2000 [online]. October 2000 [retrieved on 2008-1 1-31J. Retrieved from the Internet: <URL: http://amsacta.cib.u πιbo.it/archive/00000294/01/EuMC_4_3.pdf>; all of the disclosure, e.g., p. 2.	1
A	US 2004/0239452 A1 (Bassali) 02 December 2004 (02.12.2004)	1-3
A	US 4,673,903 A (Saad) 16 June 1987 (16.06.1987)	1-3

D Further documents are listed in the continuation of Box C. D

- ♦ Special categories of cited documents
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 October 2008 (31.10.2008)	12 NOV 200b

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Lee W. Young **PCT Helpdesk 571-272-4300** **PCT OSP 571-272-7774**