Progress In Electromagnetics Research M, Vol. 11, 153–164, 2010

THE NUMERICAL ANALYSIS OF THE PLANAR RECTANGULAR WAVEGUIDE HAVING ALTERABLE SINGLE MODE'S WORKING BANDWIDTH

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Abstract—By inserting a dielectric layer, covered by a grounded metal plane, into a hollow rectangular waveguide (HRWG), a planar rectangular waveguide (PRWG) is structured. It is a new candidate solution for both MMIC and hybrid planar RF circuit applications. An intensive numerical analysis of the PRWG is conducted by a 2-D FDTD method. The propagation characteristics of the PRWG with different physical dimensions and electrical parameters are presented. This analysis shows that the PRWG can give an alterable single mode working bandwidth for dominant mode compared with the HRWG, and the size of the transverse section of the PRWG is smaller than the HRWG under the same cutoff frequency of dominant mode.

1. INTRODUCTION

The guided wave system is very important in radio and is one of the basic topics in both electromagnetic theory and microwave as well as millimeter-wave circuit engineering.

The hollow rectangular waveguide (HRWG) is commonly used to realize low loss microwave or millimeter-wave circuit. In recent decades, some new rectangular waveguides with planar structure have appeared, such as the substrate integrated waveguide (SIW) [1–3], half mode SIW [4] and the waveguide based on the technology of LTCC [5–7]. In [8], a new plane rectangular waveguide is proposed. The new waveguide is constructed with a metal rectangular waveguide loaded with a substrate partly covered by a grounded circuit metal patch. It is called planar rectangular waveguide (PRWG).

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The single mode working bandwidth in metal waveguides is important. UWB technology may offers interesting application such as the UWB communication, UWB radar, etc. For common HRWG, the single mode working bandwidth equals the dominant mode's cutoff frequency with a side ratio $b/a = 1/2$. And for SIW and LTCC waveguide, their propagation characteristics are nearly the same as the metal rectangular waveguide having the same transverse section sizes and filled with the same dielectric.

In this paper, an intensive numerical study of the PRWG is presented by an effective 2-D FDTD. It is shown that this new waveguide can offer much larger bandwidth of single mode working (BWSMW) for dominant mode than the HRWG having the same dominant mode's cutoff frequency, and the size of the transverse section of the PRWG is much smaller than that of the HRWG. It also presents the propagation constant curves and field intensity distribution in the transverse section of the waveguide when the relative permittivity of the loading dielectric layer is increasing.

2. THE EFFICIENT 2-D FDTD

For numerical analysis of guided wave eigenvalue problem, the 2-D FDTD is a power tool which is introduced by Xiao et al. and uses only a 2-D mesh consisting of all six field components [9]. Since then much progress has been made [10–12].

This paper followed an efficient 2-D FDTD scheme [8] which not only gives the cutoff frequencies and propagation constant curves for excited waveguide modes but also can present the field-component's numerical distribution at the transverse section for each excited mode. Data of numerical field distribution of dominant mode are useful in efficient 3-D FDTD circuit analysis of guided wave system by the numerical orthogonality [14].

It should be pointed out that step 4 in [8] can only gives the field component's transverse numerical distribution, the same as the exciting field-components for each mode. All other field-components equal zero under 2-D FDTD scheme with $\beta = 0$. For example, if the excited field-component is E_x, one can get the E_x-component's transverse numerical distribution for each mode by step 4.

To obtain other field-component's transverse numerical distributions, one can follow the scheme in [13], where a band pass exciting source and numerical mode orthogonality are used.

3. RESULTS OF NUMERICAL ANALYSIS OF THE PRWG BY 2-D FDTD

The PRWG under analysis is shown in Fig. 1. This PRWG is composed of a metal rectangular waveguide with cross section: $a \times b = 15 \times 7\,\text{mm}^2$ and loaded with a dielectric layer with thickness: $h = 1.4\,\text{mm}$. Relative permittivity is ε_r. The dielectric layer is partly covered with a grounded thin metal plane. The metal plane's width is $a - nsy * dy$, where dy is space step in y-direction, and 'nsy' is an integer. In numerical simulation, the thickness of the metal plane is omitted, and it is considered as a perfect conductor.

Set $\beta = 0$, a 2-D FDTD is conducted, and the results are shown in Fig. 2. The figure gives three cutoff frequencies for the lowest order modes. They are 5.553 GHz, 9.627 GHz and 19.593 GHz respectively.

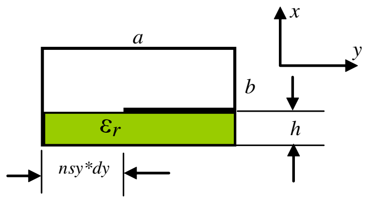

Figure 1. The planar rectangular waveguide loaded with dielectric layer. The metal plane's width equals $a - nsy * dy$. dy is the space step in y-direction. The thickness of the dielectric layer is h.

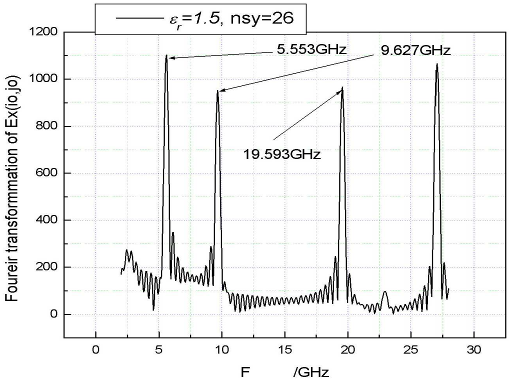

Figure 2. The cutoff frequencies of the PRWG, in which $\varepsilon_r = 1.5$, $nsy = 26$, $a = 15\,\text{mm}$, $b = 7\,\text{mm}$, $h = 1.4\,\text{mm}$. The sample point's coordinates are $io \times dx, jo \times dy$ $(io = 11, jo = 24, dx = 7\,\text{mm}/40, dy = 15\,\text{mm}/80)$.

The dominant mode's cutoff frequency is $c_0/30\,\mathrm{mm} = 9.99\,\mathrm{GHz}$ for HRWG having the same size. So the introduction of the dielectric layer, partly covered with a grounded metal plane, causes another lower mode in the PRWG.

Figure 3 shows the cutoff frequencies of the two lowest modes when the relative permittivity is changed from 1 to 9.6. These two frequencies decrease in different speeds, so there is the biggest difference at $\varepsilon_r = 4.3$. This provides the largest BWSMW about 5.63 GHz, and it is much larger than those of HRWG with the same

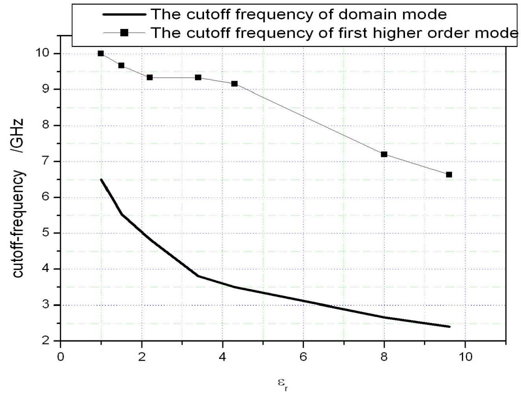

Figure 3. Cutoff frequencies for the lowest two modes of the PRWG when relative permittivity of the dielectric layer is changed.

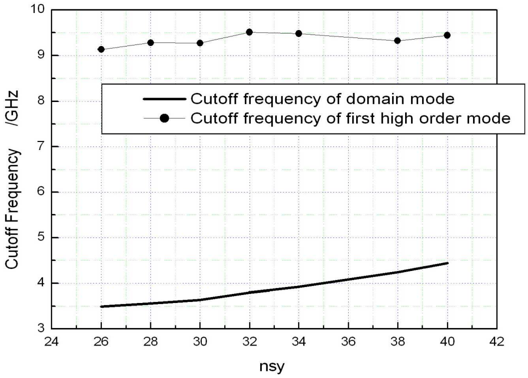

Figure 4. Cutoff frequencies for the lowest two modes of the PRWG when nsy is changed. Here the width of the metal plane is equal to $(a - nsy * dy)$.

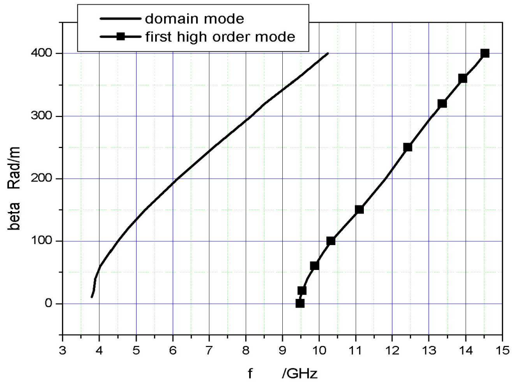

Figure 5. When $\varepsilon_r = 4.3$, $nsy = 32$, the propagation constants for lowest two modes.

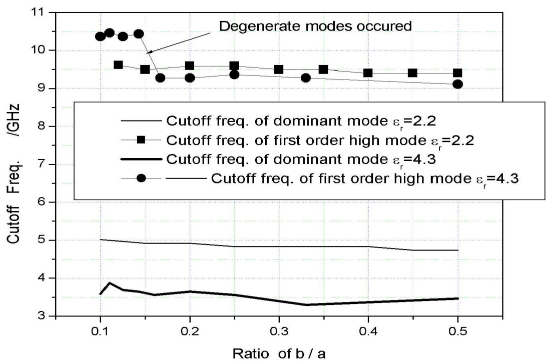

Figure 6. Cutoff frequencies of the lowest modes when the ratio of wide side to narrow side is changed.

dominant cutoff frequency, and its BWSMW is only 3.8 GHz, while the PRWG's size is smaller than the HRWG. For a HRWG, the cutoff wave length of dominant mode is

$$\lambda_{c\_TE10} = 2a = c_0/3.8\,\text{GHz} = 78.89\,\text{mm} \tag{1}$$

where 'a' is the size of wide side wall. 'a' should be 39.45 mm, and 'a' only equals 15 mm for PRWG.

Figure 4 shows the two lowest mode's cutoff frequencies when the width $(a - nsy * dy)$ of the metal plane is changed. Here, $\varepsilon_r = 4.3$, and other parameters are fixed and the same as in Fig. 3. It is shown that the largest bandwidth for BWSMW is about 5.72 GHz when $nsy = 32$.

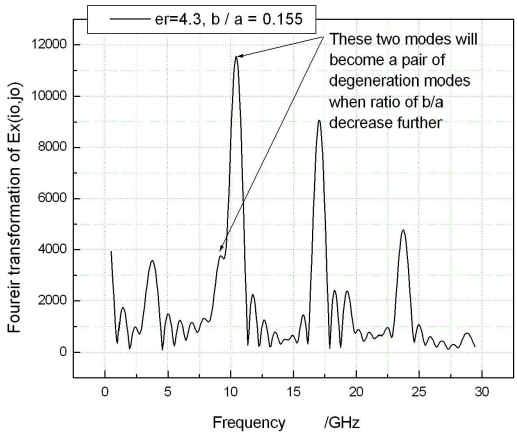

Figure 7. There is a pair of degeneration modes about 10 GHz.

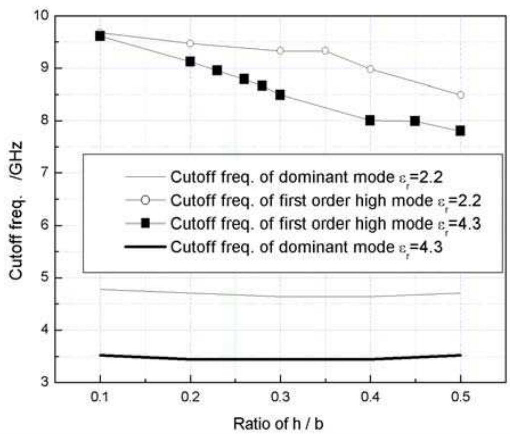

Figure 8. Cutoff frequencies of the lowest modes when the ratio of wide side to narrow side is changed.

This means that the width of the metal plane is equal to 9 mm.

Figure 5 gives the propagation constants of the two lowest modes, where $\varepsilon_r = 4.3$ and $nsy = 32$.

Figure 6 shows cutoff frequencies of the two lowest modes when the ratio of 'b' to 'a' is changed. There is a pair of degenerate modes about 10 GHz (See Fig. 7) where relative permittivity equals 4.3.

Figure 8 is the two cutoff frequencies of the lowest modes when the ratio of 'h' to 'b' is changed.

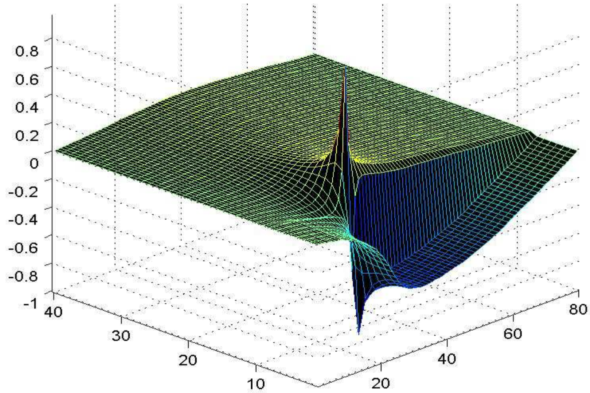

Figure 9. Field distribution on the transverse section of the dominant mode's E_x-component when $\varepsilon_r = 1.5$.

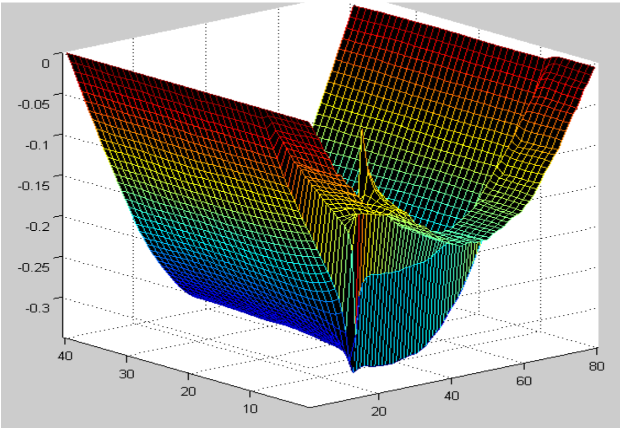

Figure 10. Field distribution on the transverse section of the first higher mode's E_x-component when $\varepsilon_r = 1.5$.

According to the numerical simulation, the lowest mode's six field-components are not equal to zero, but the E_z-component is very small compared with transverse electric components, so one considers the dominant mode as the quasi-TE mode, for the dominant mode of the PRWG.

Figure 9 and Figure 11 show field distribution on transverse section of three lower modes E_x-components when $\varepsilon_r = 1.5$.

Figure 12–Figure 14 show field distribution on transverse section of three lowest mode E_x-components when $\varepsilon_r = 4.3$.

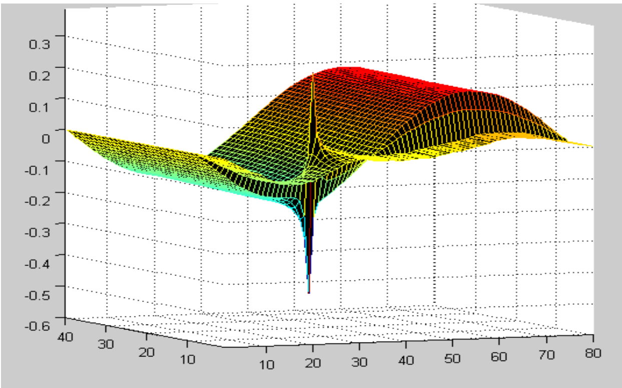

Figure 11. Field distribution on the transverse section of the second higher mode's E_x-component, when $\varepsilon_r = 1.5$.

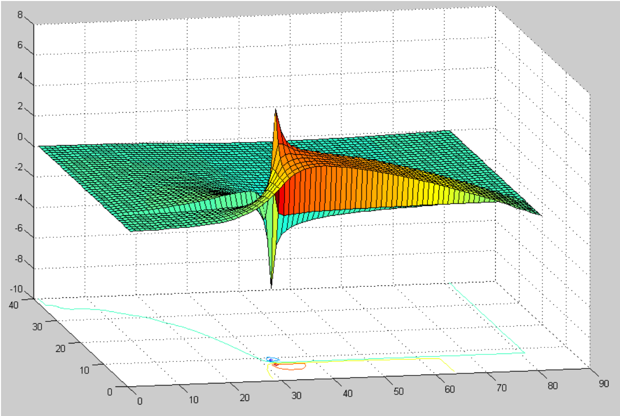

Figure 12. Field distribution on the transverse section of the dominant mode's E_x-component when $\varepsilon_r = 4.3$.

These six pictures (Figures 9–14) show that the EM-energy mainly storing in air layer moves to the dielectric layer of the PRWG when the relative permittivity increases from 1.5 to 4.3 for higher order modes. The EM-energy's location keeps unchanging, and it is mainly located under the metal plane, for dominant mode.

This prompts that one can design various circuits on the metal plane in a wide (dominant mode) single mode working band.

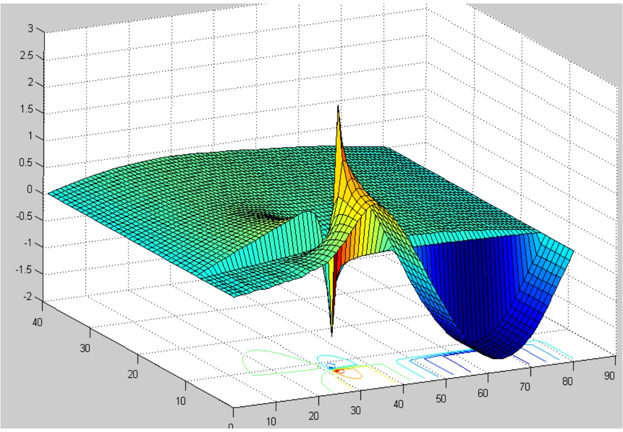

Figure 13. Field distribution on the transverse section of the first higher mode's E_x-component when $\varepsilon_r = 4.3$.

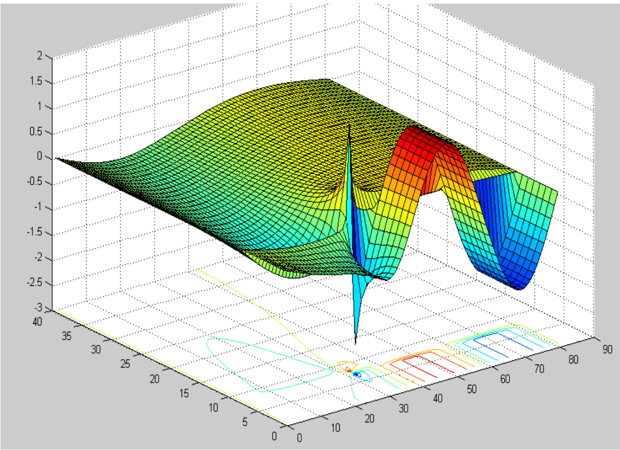

Figure 14. Field distribution on the transverse section of the second higher mode's E_x-component, when $\varepsilon_r = 4.3$.

4. SOME DISCUSSION

From above results of numerical analysis, it is shown that

1. There is the largest BWSMW for dominant mode, when dielectric's relative permittivity or the width of the grounded metal plane of the PRWG changes while other structures' parameters are fixed.

2. When the ratio of 'b' to 'a' is increasing, the BWSMW is changed slowly except a pair of degenerate modes appears.
3. The BWSMW decreases when ratio of 'h' to 'b' increases.
4. For cases 2 and 3, one always got a larger BWSMW, when a dielectric layer with bigger relative permittivity is chosen. So one can design a PRWG with a specific BWSMW without changing the transverse size of the waveguide.
5. The main EM-energy is located under the grounded metal plane for the dominant mode, and it works as transmission line mode.

The inserting metal plane not only is a part of the PRWG, but also provides the circuit design space, which offers more flexible design for applications.

5. CONCLUSION

This paper presents an intensive numerical analysis of the PRWG with the effective 2-D FDTD. The analysis shows that the proposed PRWG can present much larger BWSMW compared to HRWG with the same size, and it is possible that one can change the BWSMW without changing the transverse size of the waveguide. Compared with HRWG, the PRWG provides much smaller size of waveguide circuits for the same cutoff frequency of dominant mode.

ALike plane transmission lines, such as the microstrip and CPW, the main EM-energy of the dominant mode of the PRWG is under the metal plane near the metal plane edge region. The unsymmetrical characteristics and planar structure of the PRWG bring new design flexibility. It will present a new kind of application for microwave components.

The introduction of dielectric layer, partly covered by metal plane, provides some new choices for circuit design. It has a plane metal and offers a possibility for a plane circuit design which is compatible with common planar RF circuit on substrates.

The structure of dielectric layers, partly covered by grounded metal, can also be used in MMIC.

It is foreseeable that various new RF circuit applications with the new plane rectangular waveguide will appear in future.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (NSFC) under grant 60871058.

REFERENCES

1. Bohorquez, J. C., H. A. F. Pedraza, I. C. H. Pinzon, J. A. Castiblanco, N. Pena, and H. F. Guarnizo, "Planar substrate integrated waveguide cavity-backed antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 1139–1142, 2009.
2. Wu, L.-S., X.-L. Zhou, Q.-F. Wei, and W.-Y. Yin, "An extended doublet substrate integrated waveguide (SIW) bandpass filter with a complementary split ring resonator (CSRR)," *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 12, 777–779, Dec. 2009.
3. Wu, L.-S., X.-L. Zhou, and W.-Y. Yin, "Evanescent-mode bandpass filters using folded and ridge substrate integrated waveguides (SIWs)," *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 3, 161–163, Mar. 2009.
4. Liu, B., W. Hong, Y. Zhang, J. X. Chen, and K. Wu, "Half-mode ubstrate integrated waveguide (HMSIW) double-slot coupler," *Electron. Lett.*, Vol. 43, No. 2, Jan. 18, 2007.
5. Wu, K.-L. and Y. Huang, "LTCC technology and its applications in high frequency front end modules," *Proceedings of 2003 6th International Symposium on Antennas, Propagation and EM Theory*, 730–734, Oct. 28–Nov. 1, 2003.
6. Lecheminoux, L. and N. Gosselin, "Advanced design, technology & manufacturing for high volume and low cost production," *IEEE/CPMT/SEMI 28th International Electronics Manufacturing Technology Symposium, 2003. IEMT 2003.*, 255–260, Jul. 16–18, 2003.
7. Mulln, T., W. Ehrhardt, K.-H. Drue, A. Gross, and L. Abahmane, "Optical-fluidic sensors in LTCC-technology," *International Students and Young Scientists Workshop on Photonics and Microsystems*, 54–57, Jul. 8–10, 2007.
8. Yu, Z. Y., X. Yang, and Q. F. Shi, "A new kind waveguide with a plan structure," *International Conference on Microwave and Millimeter Wave Technology, 2008. ICMMT 2008.*, Vol. 1, 311–314, Apr. 21–24, 2008.
9. Xiao, S. and R. Vahldieck, "An efficient 2-D FDTD algorithm using real variables," *IEEE Microwave Guided Wave Lett.*, Vol. 3, 127–129, May 1993.
10. Asi, A. and L. Shafai, "Dispersion analysis of anisotropic inhomogeneous waveguides using compact 2D-FDTD," *Electron. Lett.*, Vol. 28, 1451–1452, Jul. 1992.
11. Zhao, Y.-J., K.-L. Wu, and K.-K. M. Cheng, "A compact 2-D

full-wave finite-difference frequency-dominant method for general guided wave structures," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 7, 1844–1848, Jul. 2002.

12. Hong, I. P. and H. K. Park, "Dispersion characteristics of a unilateral fin-line using 2D FDTD," *Electron. Lett.*, Vol. 32, 1992–1994, Oct. 1996.
13. Yu, Z. Y., "The general numerical method of analysis of waveguides of arbitrary cross section with perfect conducting wall by FDTD and its applications," *Journal of Electromagnetic Waves and Applications*, Vol. 17, No. 7, 1063–1073, 2003.
14. Yu, Z. Y., "A new method of S-parameter extraction from the FDTD analysis of microstrip circuit discontinuities," *Microwave and Optical Technology Letters*, Vol. 16, No. 3, 162–163, Oct. 20, 1997.