Development of a Variable Optical Attenuator (VOA) Using MEMS Technology

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ABSTRACT With the rapid increases in traffic on optical telecommunications systems, there is an active program for developing transmission devices for use in wavelength division multiplexing (WDM), which is becoming the mainstream technology for providing higher transmission speeds and a larger number of signal channels. It has been proposed that in the WDM systems of the future, variations in power due to wavelength could be reduced and the quality of transmission improved by adjusting the power after demultiplexing into individual signal wavelengths. It is envisaged that the current method, in which the power of all the multiplexed optical signals is adjusted by a single variable optical attenuator (VOA) would give way to a method in which one VOA is used for each wavelength. Given the number of multiplexed wavelengths, this change will require VOAs that are considerably more compact. This paper reports on the development of a VOA that has loss characteristics of low wavelength dependence and can also be used with multiplexed signals, and employs micro-electromechanical system (MEMS) technology, occupying only 1/25th the space of conventional devices.

1. INTRODUCTION

To cope with recent rapid increases in telecom traffic, there has been a rapid deployment in the field of fiber-optic transmission using wavelength division multiplexing (WDM), in which a number of signals of differing wavelength are multiplexed for transmission on a single fiber. In existing WDM transmission systems, transmission path loss is compensated and relaying effected by erbium-doped fiber amplifiers (EDFAs), which can batch amplify the multiplexed signal made up of numerous individual wavelengths. EDFA amplification gain, however, is wavelength-dependant in the bands used in WDM communication, and so to maintain a constant reception level for each wavelength, the method most commonly used to maintain a flat transmission bandwidth is to use a gain equalizer (GEQ), having a wavelength dependence profile that is the inverse of the EDFA [1].

But when there is a change in optical input power to the EDFA due to a change in span loss in the transmission path or add-drop multiplexing of the optical wavelength signal (OADM), the wavelength dependence of the EDFA gain profile changes, and since the profile of the GEQ is fixed, there is a shift in the flattening effect it provides. This makes it necessary to use an optical device known as a variable optical attenuator (VOA), which can realize a flattened gain profile by applying to the EDFA and GEQ an optical power adjusting function that has low wavelength dependence [2]. Even with this method using a VOA, however, the adjustment is applied to the multiplexed signal as a whole, so that in order to satisfy the needs for communication system upgrades and greater accuracy in the future, it has become necessary to use VOAs for each wavelength after the multiplexed signal has been demultiplexed. It is anticipated that in WDM systems, the number of multiplexed wavelengths will increase from several dozen at present to several hundred, so that to use a single VOA for each wavelength requires that each VOA be extremely compact. It seems likely that realizing a VOA that is both compact and low in wavelength dependence will increase the degree of freedom in designing systems, leading to greater demand.

Against this background we have developed a VOA using micro-electromechnical system (MEMS) technology with loss characteristics that have low wavelength dependence.

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2. DEVELOPMENT TARGETS

Table 1 shows the target values for the VOA development project. With respect to the wavelength band, we aimed at low wavelength dependence, envisaging application for signals demultiplexed into single wavelengths, as well as in current applications, in which the multiplexed signals are batch adjusted. We have therefore taken account of the fact that EDFA bandwidth has been extended from the

Table 1 Target specifications for MEMS-type VOA.

Optical characteristics	
Wavelength bands	C (1530~1565 nm) and L (1565~1625 nm)
Insertion loss	<1.0 dB
Return loss	>45 dB
Wavelength flatness	0.3 dB (in C- or L-band)
Polarization-dependent loss	<0.3 dB (less than 1% of loss)
Temperature dependence	<0.15 dB
Driver and other characteristics	
MEMS actuator	Electrostatic drive system
Operating voltage	<200 V
Loss resolution	<0.1 dB
Repeatable setting accuracy	<0.1 dB
Dimensions (L×W×T)	10.0×2.0×0.6 mm
Package size (L×W×T)	33×6.5×4.5 mm
Sealing	Hermetic sealing

C-band (1530~1565 nm) to the L-band (1565~1625 nm), and made it applicable to both these bands. (Because of measuring equipment limitations, 1530~1620 mn was used in actual measurements and evaluations).

In setting the development targets in Table 1, we aimed at broad equivalence with the characteristics of existing VOAs.

We also aimed at an operating voltage of less than 200 V. For the MEMS chips themselves we adopted an electrostatic drive system, reducing the power consumption of the chips themselves. The electrostatic drive system requires a high voltage, but since there is fundamentally no flow of current (although leakage current is present), the typical power consumption is in the microwatt order. Thus the power consumption of the module itself is determined more by the consumption of the voltage step-up circuit than by the MEMS chip. To prevent condensation to the MEMS chip, a hermetically sealed package was used.

3. STRUCTURE OF MEMS-TYPE VOA

Single-mode fiber (SMF) was used at the input and output of the VOA developed here, with a graded index fiber (GIF) having the same diameter--125 μm--as the SMF fusion spliced for a specified length, to form an optical coupling with a lens function. An anti-reflection (AR) coating is applied to the tip of the GIF. The GIF tip is polished at an angle so that the light beam emitted from the end of the GIF is not aligned with the optical axis of the fiber, but is at an angle to it. This angled optical beam is interrupted by means of a shutter that has been formed by inductively-coupled plasma deep reactive ion etching (ICP-DRIE).

The MEMS chip uses a silicon-on-insulator wafer, with the shutter, actuator and fiber grooves formed simultaneously on the chip by ICP-DRIE, followed by metal vapor deposition over the whole chip.

The actuator of the MEMS chip is of the comb type, and the GIF is held in the fiber grooves by means of adhesive.

Photo 1 SEM image of MEMS chip.

The MEMS chip with this GIF optical coupling system is fixed by adhesive within a casing, which is hermetically sealed. Photo 1 is a SEM image of the MEMS chip.

4. DESIGN

4.1 Optics

In designing this MEMS-type VOA, it was decided, in order to take maximum advantage of the small size of the MEMS chip, to make the collimator the same size as the optical fiber thereby reducing the size of the module. Accordingly a GIF coupling system was designed in which an all-core GIF was given the function of lens and was fusion spliced for a specified length to the tip of the SMF. In this design there was some discussion as to whether the VOA should be of the light shielding type or the tilted mirror type. It was understood that with the light shielding type the wavelength dependence of loss could be reduced by modifying the shape of the shutter [3], but with the tilted-mirror type, because of the wavelength dependence of the mode field diameter of the fiber, the wavelength dependence of the loss would be greater than for the light shielding type.

Figure 1 shows the result of simulations of wavelength-dependent loss for a tilted mirror type and a light shielding type that interrupts the light beam from one side using results of measurements of SMF mode field diameter. (Taking loss at 1530 nm as the reference, the difference

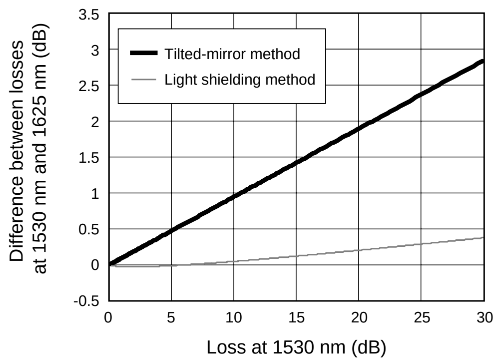

Figure 1 Result of simulations of wavelength-dependent loss.

from loss at 1625 nm is plotted; for other light shielding types, see reference 3.) With the light shielding type, however, to reduce the influence of diffraction at a portion of the shutter, the diameter of the light beam must be increased, necessitating a larger movement of the MEMS actuator, while with the tilted mirror type a large loss can be achieved with a small movement. Since the objective of this work was to develop a VOA with lower wavelength dependence of loss, the light beam shielding type was adopted.

The spot size from the light beam emitted was designed to be the maximum spot diameter obtainable from the GIF optical coupling system used. And for the GIF facet to achieve a return loss of -45 dB or better, angled polishing was used. In this way the light beam is emitted from the end facet of the GIF at an angle calculated by Snell's law. Thus the GIF optical coupling system must not be opposed in a straight line, but in an offset position. The fiber grooves to the left and right are thus fabricated with an offset that is determined from the angle of emission of the beam and the opposed distance. These offset fiber grooves were formed in one operation on the MEMS chip.

As a result of measurements of the beam actually emitted from the GIF using a near field pattern (NFP) system, it was confirmed that the beam diameter and opposed distance were in accordance with the design. Figure 2 shows an image of the near-field pattern of the GIF specially fabricated in this work, by a process in which an all-core GI preform was drawn to the same diameter as SMF.

4.2 MEMS Chip

The MEMS chip is fabricated by micromachining of a silicon wafer, but even so, it is still a mechanical structure with moving parts that could be damaged by mechanical vibration or impact.

Accordingly simulations were run to confirm that moving parts were not subject to breakdown by the application of vibration or in impact tests.

Specifically, we considered that in the Telcordia test for vibration (GR-1221) breakdown did not occur under 6 axis, 20 G, 20 to 2000 Hz. Similarly with respect to impact, considering that breakdown did not occur when subjected to 6 axis, 500 G impacts in the Telcordia impact test, it was confirmed by simulation that during application of a 500 G impact, the weakest part of the comb did not made contact with the structure. In the simulation, under an impact of 500 G the moving parts moved in the direction of movement of the shutter but the teeth of the comb did not made contact with each other, and with respect to the opposite direction, the rigid portion of the truss structure of the spring made contact with the electrode, but this portion was strong enough that it was not damaged. Further the movement in the two planes perpendicular to the direction of movement of the shutter was less than 1 μm and design was such that the moving parts made no contact whatever with other structural components.

5. RESULTS FROM PROTOTYPES

Photo 2 shows the appearance of the MEMS-type VOA module developed in this work. The development targets in terms of dimensions were achieved: 6.5 mm in width, 33 mm in length (fiber retaining boot length 5 mm), and 4.5 mm in height. The module was sealed by means of nitrogen gas encapsulation.

5.1 Optical Characteristics

5.1.1 Insertion Loss

The insertion loss of the prototype MEMS-type VOA module using a 1550-nm light source had an average value of 0.6 dB, easily satisfying the design target of 1 dB. This loss depends on the accuracy of the alignment between the opposed collimators, but these results demonstrate that the fiber grooves formed in a single operation on the silicon substrate were very accurately made.

5.1.2 Return Loss

Figure 3 shows the wavelength dependence of return loss at several values of attenuation by the insertion of the shutter at the incidence port. Since it is anticipated that in a structure in which the light beam is interrupted by the shutter some reflection from the shutter will occur in the attenuation range, the return loss was measured at an attenuation of 10, 20 and 30 dB. Over the whole range of attenuation the levels of return loss obtained presented no practical problems.

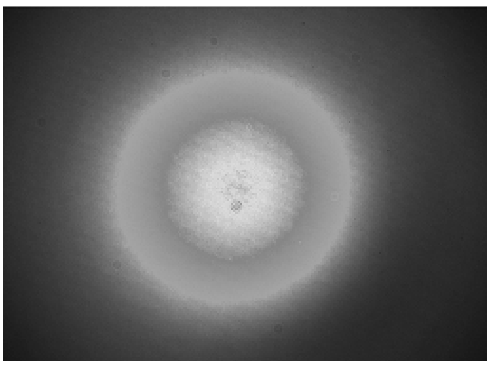

Figure 2 Image of near-field pattern of GIF.

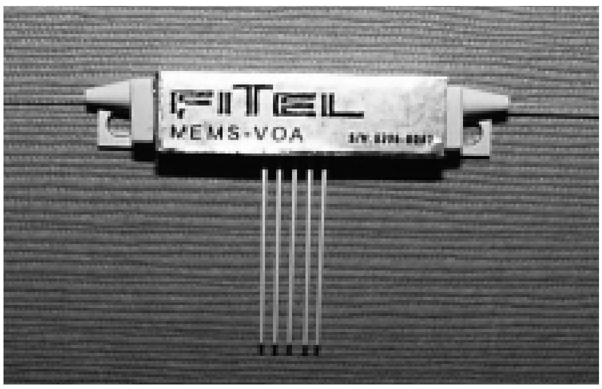

Photo 2 Appearance of MEMS-type VOA module.

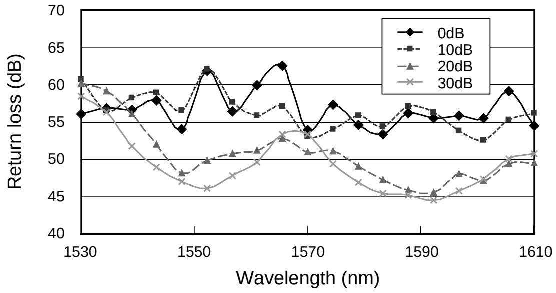

Figure 3 Wavelength dependence of return loss at several values of attenuation by shutter. (at incidence port)

5.1.3 Wavelength Characteristics

Figure 4 shows the wavelength dependence of loss at selected values of attenuation. It was confirmed that the target value for band flatness (maximum loss minus minimum loss) for an attenuation range of up to 25 dB for both C- and L-bands was within 0.3 dB. Further, at an attenuation range of up to 20 dB, even across a broad band including both the C- and L-bands, it was confirmed that flatness came within 0.3 dB. Also no periodic ripples were observed in this spectrum. This flatness showed good agreement with the results of simulations of the wavelength dependence of SMF mode field diameter. The simulation yielded the fact that this good wavelength flatness is not obtainable with a collimator having an ordinary aspheric lens, and in actual measurement as well, the wavelength unevenness obtained using the GIF coupling system of this work was approximately 1/3 the results with a collimator using an ordinary aspheric lens.

5.1.4 Polarization-dependent Loss (PDL)

Figure 5 shows the attenuation dependence of polarization-dependent loss (PDL) in terms of average values of PDL measured at 5-nm intervals from 1530 to 1620 nm. At an attenuation of up to about 10 dB PDL deteriorated sharply, while at higher attenuation results of approximately 0.3 dB were obtained. In fundamental experiments using the same GIF optical coupling system and a razor with an extremely sharp blade as the shutter, PDL characteristics were extremely good--less than 1% of attenuation.

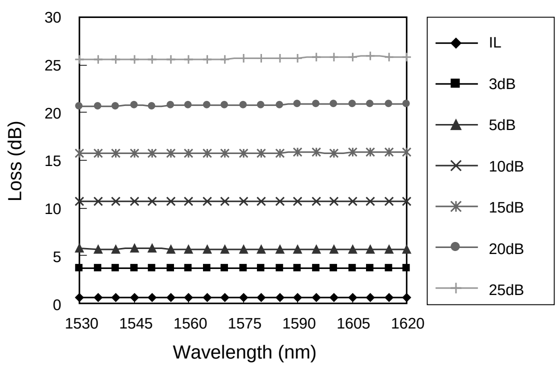

Figure 4 Wavelength dependence of loss at selected values of attenuation.

5.1.5 Temperature Dependence

Figure 6 plots data showing the temperature dependence of insertion loss at temperatures of from -45 to +85°C. Only about 50 hours are covered by the graph shown but in fact tests were carried out for two weeks yielding an equivalent results. It can be seen that the variation in insertion loss was held to within ±0.10 dB, which was less than the development target of 0.15 dB. The temperature dependence is attributed to the method used to anchor the GIF, and good results for GIF anchoring were achieved by adjusting the amount of epoxy adhesive used, the position of attachment, and the area of attachment.

5.2 Operating Characteristics

5.2.1 Voltage Dependence of Attenuation

Figure 7 shows the relationship between voltage and attenuation during operation of the MEMS-type VOA. The relationship obtained in simulations is also plotted on the same graph. As can be seen the simulation and actual measurements are in extremely good agreement, and since voltage setting accuracy can be obtained to the millivolt order, the error in attenuation adjustment is 0.1 dB or less. Note that the MEMS chip itself is capable of analog operation, so that the accuracy of attenuation setting is dependent on the setting accuracy of the voltage circuit.

5.2.2 Switching Time

In terms of measuring switching times, assuming an application for the adjustment of gain level inside the EDFA, several decibels may be considered an appropriate varia-

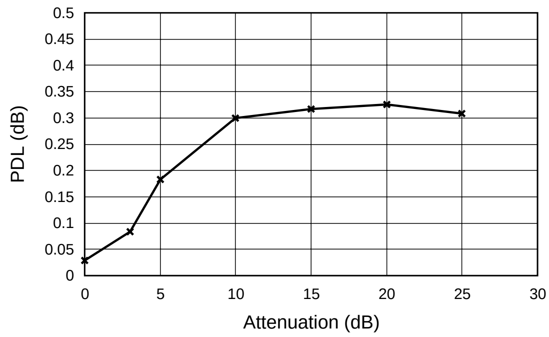

Figure 5 Attenuation dependence of PDL.

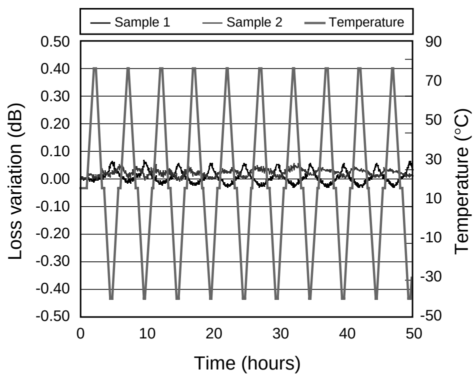

Figure 6 Temperature dependence of insertion loss.

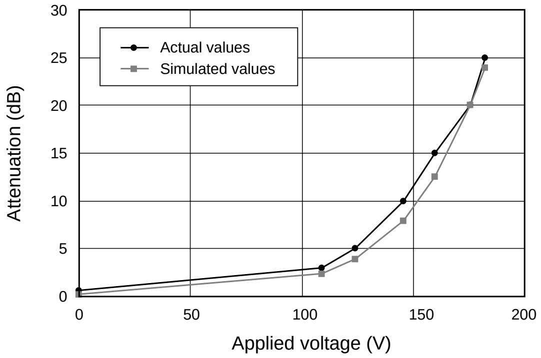

Figure 7 Voltage dependence of attenuation.

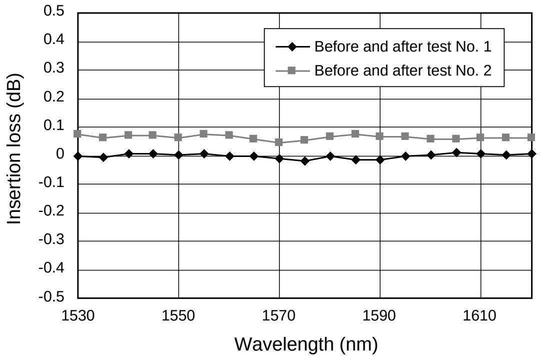

Figure 10 Change in insertion loss before and after vibration tests.

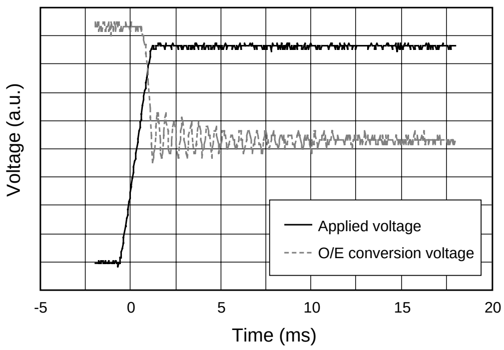

Figure 8 Switching time of insertion loss to 3-dB attenuation. (in air)

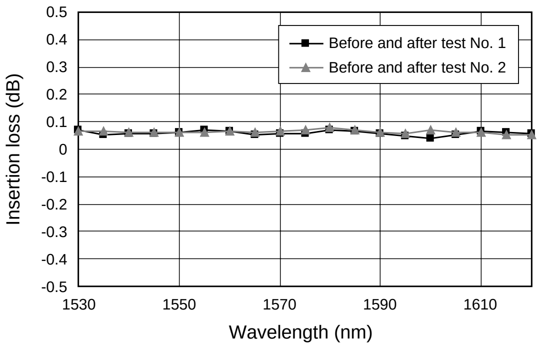

Figure 11 Change in insertion loss before and after impact tests.

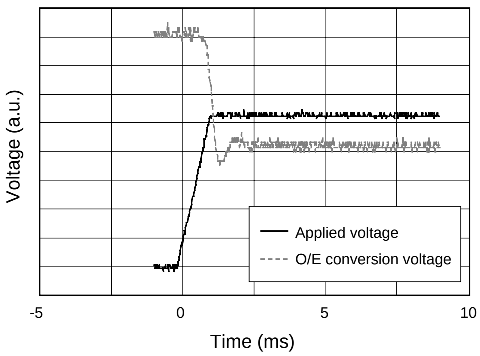

Figure 9 Switching time of insertion loss to 3-dB attenuation. (in matching oil for damping)

tion in attenuation. Measurements were therefore made of the switching time required for an attenuation variation of 3 dB. Measurements were made using a 2-channel digital storage oscilloscope, with the input to one channel being the O/E conversion of the light from the output port of the MEMS-type VOA module, and the input to the other channel being the voltage applied to the MEMS chip. Figure 8 shows the results.

During application of the voltage, attenuation oscillated in the neighborhood of 3 dB, and it required about 15 to 20 ms for the oscillation to stabilize. We attribute this to the lively movement occurring at the point of equilibrium between the spring and electrostatic force. This oscillation can be suppressed by injecting into the case a liquid such as matching oil, which offers viscous resistance. Figure 9 shows measured values for switching time when matching oil was introduced. In these results switching time was approximately 2 ms.

6. RELIABILITY TESTING

6.1 Telcordia Tests

The following sections present the results of Telcordia tests (GR-1209 and -1221) performed to test the reliability of the MEMS-type VOA developed here.

6.1.1 Mechanical Tests

Figures 10 and 11 show changes in insertion loss before and after two modules were subjected to a vibration test (20~2000 Hz, acceleration 20 G) and an impact test (acceleration 500 G, 6 axes, 5 times).

The amount of change after the mechanical tests was less than 0.1 dB. No damage was observed to the MEMS chips which, as the simulation predicted, passed the Telcordia mechanical tests.

6.1.2 Operating Behavior in Vibration Environment

To test device behavior when subjected to vibration during operation as set forth in Telcordia GR-63 for office vibration, the change in attenuation was measured under an

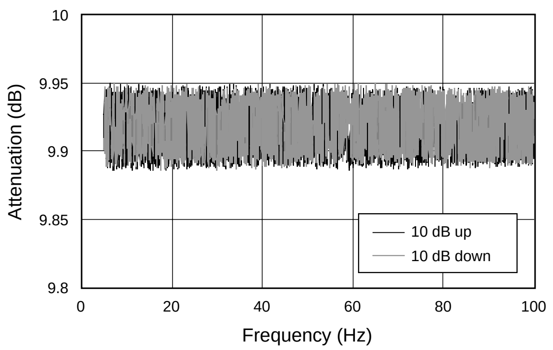

Figure 12 Change in attenuation near 10 dB when acceleration and vibration added in Y direction.

attenuation of approximately 10 dB due to application of voltage, scanning in both directions for 10 min for 5~100 Hz in the direction of shutter movement with an acceleration of 0.1 G (19 Hz/min). Results are shown in Figure 12.

The “up” and “down” in the graph refer to an increase or decrease in frequency. These results showed no difference between “up” and “down”, and the characteristics were extremely stable--only about ±0.03 dB with an attenuation of 10 dB.

6.1.3 Environmental Tests

As tests under specific conditions of temperature and humidity the following tests are scheduled to be conducted: temperature/humidity aging test (GR-1209: 85°C RH85% for 14 days), temperature/humidity cycling test (GR-1209: -40~+75°C, RH10~80%, 42 cycles for 14 days), high-temperature/high-humidity storage (85°C, RH85% for 2000 hr), high-temperature storage (85°C for 2000 hr), and low-temperature storage (-40°C, RH85% for 2000 hr). The modules are hermetically sealed, and judging by the results of temperature dependence tests presented above, no problems are anticipated.

7. CONCLUSION

A compact MEMS-type VOA has been developed which offers outstanding attenuation-wavelength characteristics and allows external control of attenuation by means of an electrical signal to adjust for dynamic variation in loss in the transmission path. It was confirmed that the following characteristics, which were the values targeted in the development, were satisfied:

Wavelength bands	C (1530~1565 nm) and L (1565~1625 nm)
Insertion loss	<1 dB
Return loss	>45 dB
Wavelength flatness	0.3 dB (in C- or L-band @ 25 dB) 0.3 dB (in C- or L-band @ 20 dB)
Temperature dependence	<0.15 dB
Loss resolution	<0.1 dB
Repeatable setting accuracy	<0.1 dB
Dimensions (L×W×T)	33×6.5×4.5 mm

The reliability of the MEMS-type VOA was tested using Telcordia tests, and it was confirmed that the results were satisfactory.

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