КАФЕДРЕ ФИЗИЧЕСКИХ ОСНОВ ЭЛЕКТРОННОЙ ТЕХНИКИ – 50 ЛЕТ

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DWDM COMMUNICATION SYSTEMS BASED ON MULTIFREQUENCY LASER RADIATION

Introduction

The main limitation in current DWDM systems is the number of physical channels through which information is transmitted. “Physical channel”, in this case, means the optical frequency which, when modulated, allows the transfer of information. The current limitations of such systems are due to the use of laser sources and frequencies that are not stable and may arbitrarily vary within a certain range. Such systems require the frequency separation between channels to be set large enough so that the frequency of adjacent channels will not overlap. As a result, the possibility of increasing the volume and speed of data transfer through existing fiber optic systems is a topic constantly discussed in the literature [1]. For increasing the amount of information transmitted in DWDM systems is an obvious of increasing the number of physical channels in one single-mode fiber.

The International Telecommunications Union (ITU-T) has developed a frequency plan [2], on the basis of which in upon which DWDM systems use a discrete set of semiconductor lasers with a base frequency of 193,100 *GHz* (λ = 1552,52 *nm*), and the remaining frequencies being separated from the base of 100 *GHz*. Thus, the width of each frequency band of 100 GHz, which leads to the 105 standard channels of ITU-T is in the range 1521,02-1605,74 *nm*.

The quality of the WDM / DWDM systems depends on the performance of discrete laser sources. According to the ITU, each of source is configured for a specific channel (width of 100 GHz). In fact, frequency stabilization of semiconductor lasers is achieved by adjust the operating temperature at which the frequency of the laser will remain within the selected range of an individual channel. Another important aspect of the existing data is the system of modulation and demodulation of the radiation.

Using modulators and demodulators results in an optical frequency deviation in the information signal of about 0.8 *nm*. Separation into narrower channels, however, increases the complexity of the modulation systems needed. This means that further development of WDM / DWDM systems to increase the capacity of transmitted data will require new modulators that can provide modulation of smaller bandwidth channels (e.g. 50 *GHz* (0.4 *nm*), 25 GHz (0.2 *nm*) or even 10 GHz (0.08 *nm*)).

All of this suggests that the most promising direction of expanding WDM / DWDM systems lies in finding and developing new physical principles that allow for modulation in increasingly narrow optical channels without affecting adjacent channels. It must be noted that increased stability of the emission frequency of semiconductor lasers, while technically and economically challenging, is also a prerequisite.

Therefore the overriding task is to look for an alternative methodology – similar to the frequency plan of the ITU-T – but that does not use semiconductor lasers. While there are some discussions of this in the literature [3], the exact conditions of such alternatives have not been described. In this paper the conditions are explored for forming such optical grid frequencies for use in DWDM systems.

The theoretical basis for building grid freguency

Requirements of the femtosecond laser in DWDM systems are directly associated with the spectral region in which such DWDM system work. These systems operate in the 1521,02-1605,74 *nm* range such as fiber lasers based on erbium-doped fiber, which provides a frequency in the region of 1.54 μm. If this laser were to generate femtosecond pulses, its frequency spectrum could cover the entire standard band scheme of the ITU. In such a case, the entire frequency spectrum could be stabilized by a single external optical frequency standard. As such, it could be used as the preferred system for telecom laser stabilized by acetylene or with the broad spectrum of radiation at the fundamental frequency stabilized Nd: YAG laser frequency stabilization with the second harmonic of the peaks of saturated absorption in iodine.

However, several unsolved technical and physical problems preclude the application of femtosecond lasers. One of the main requirements is to stabilize the frequency of a fiber femtosecond laser. Doing this will provide simultaneous stabilization of frequencies of all harmonics of the laser.

The time during which all modes are synchronized defines the pulse duration.

The emission spectrum of the femtosecond laser is in the discrete spectrum of optical frequencies that are defined by the specifications of the laser itself. As the generated pulses are limited in their spectrum, there are literally thousands of harmonics that may be emitted depending on the duration of the pulse. Using a fiber photonic crystal, it is possible to implement compression pulses to cause a spectral expansion, – i.e. increasing the number of spectral components [4]. In the reviews [5, 6] can find a more detailed description of the femtosecond laser.

The interval between two adjacent frequencies in frequency spectrum depend on length of laser resonator L, therefore intermodal interval value can be determined by

$$\Delta f = c/2L. \tag{1}$$

Thus, depending on the length of cavity Δf can range from 50 MHz to 1 GHz and more.

Fig. 1 shows the theoretical model of the emission spectrum of the femtosecond laser, which is defined by two parameters - f_r и f_{ceo} (see Fig. 1);

- f_r (r-repetition) – distance between two adjacent frequency components.
- f_{ceo} (ceo-carrier envelope offset), the frequency shift defines by the difference between the phase and group velocity of light in the laser cavity.

$$f_r = v_g / 2L, \tag{2}$$

where L – length of cavity, a v_g – the group velocity of the radiation in the resonator.

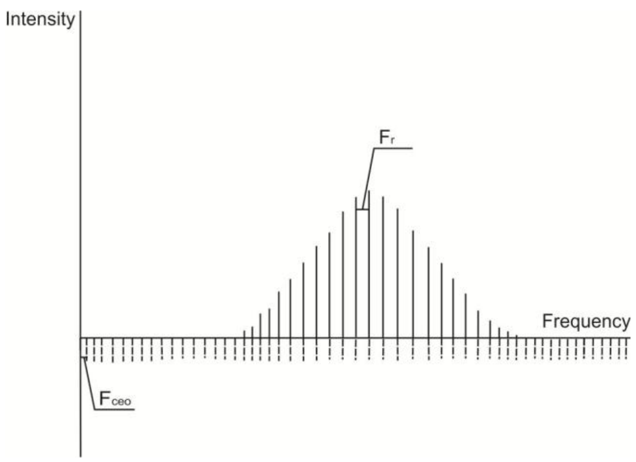

Fig. 1. Spectrum of femtosecond laser

The frequency of each individual component of the discrete spectrum is determined by its number N and the interval between the peaks f_r and f_{ceo} – shift peak with N = 1 "ideal" frequency grid overlaying the entire frequency range, relative to $f = 0$.

$$f_N = Nf_r + f_{ceo};\qquad (3)$$

f_r can be determined experimentally from the spectrum of the multi-frequency detection signal femtosecond laser by homodyne scheme [7]. Otherwise, f_r can be determined by direct measurement using high frequency metering of the minimum frequency of beats between the harmonics of femtosecond laser;

f_{ceo} can be determined using an external optical frequency frame [8].

To use each of the spectral components of pulsed femtosecond laser f_N as an optical frequency DWDM systems requires, (a) to determine the frequency distance between them, i.e. set the value f_r; and (b), to ensure the stability of the absolute values of frequencies f_N. Value f_r actually forms the band plan for DWDM systems, similar to ITU-T, but on a completely new physical basis. Complementing the femtosecond laser stabilization systems' f_r and f_{ceo} values, i.e. the stabilization systems cavity length and comparing the frequency of one of the frequency harmonics to the external frequency standard, a solution is reached in time for a stable generated frequency plan.

Each harmonic of the femtosecond laser, during creation of the channel plan will represent a single physical channel. If the distance between adjacent channels is in the 5GHz range, the length of the cavity would be about 30 *mm*. But since the development of lasers with a smaller cavity length is an independent technical problem, the formation of a channel plan with the emission spectrum of the femtosecond laser is an easier way to implement thinning of the spectrum than building a laser with a short cavity.

The use of optical frequency selector like Fox-Smith allows you to emphasize the harmonics spaced at the required frequency range. The selector allows one to select the frequency in the spectrum of those spectral components that will ensure the formation of a channel plan, the relevant ITU-T. The distance between frequency channels will be equal mf_r, where $m \gg 1$.

Regardless of the principles of the frequency plan of DWDM systems, frequencies f_r and f_{ceo} of the femtosecond laser should be stabilized. Well-known results on the stabilization of the frequency spectrum of the femtosecond laser [9] used to measure optical frequencies. However, the question of the stability of the emission spectrum of the femtosecond laser, as the grid frequency band plan implements the same ITU-T, the literature has not yet been fully argued.

The emission spectrum of a femtosecond laser and features of its stabilization

Wavelength range, which is used in the DWDM systems, is used to impose restrictions on the use of active media in femtosecond lasers. Therefore, there are at least two variants of media that provide the generation of femtosecond pulses in the near-infrared (1300 – 1600 *nm*) range. The chromium laser: forsterite (Cr_4 +: Mg_2SiO_4), which ensures the generation of a range of 1.3 microns, and the chromium-yttrium aluminum garnet (Cr4 +: YAG) laser, operating in the range of 1.5 microns. In addition there are compact solid-state lasers used in optical communications, fiber amplifiers and lasers, the active media activated with erbium (Er). In this paper we use a titanium: sapphire (Ti: Sapphire) laser with an emission spectrum extended by photonic crystal fiber [10].

As noted above, the use of the frequency spectrum for DWDM systems is possible if the grid frequency is stabilized with respect to a highly stable frequency standard. A frequency standard which is designed for optical communications and can be recommended for the task based on a semiconductor laser with a wavelength of 1542 *nm* – the frequency of which is stabilized by the lines P (16) absorption $^{13}C_2H_2$ acetylene [11]. The relative standard uncertainty with which one can establish the absolute frequency (wavelength) of the radiation is $5{,}2\ 10^{-10}$. For synchronization of the frequency spectrum of the femtosecond laser, that laser has all the necessary parameters – wavelength(operate on 1554 *nm*), power about 10*mW*. The only problem associated with its use is that these lasers are not currently available on a commercial scale. Consequently, to ensure synchronization of the femtosecond laser in DWDM systems will require more manufacturing and research of femtosecond lasers.

Another solution to ensure the synchronization of the frequency spectrum of the laser in this range is the use of commercially available chip lasers Nd: YAG/127I2 (these lasers are also included in the list of standard frequency) frequency-stabilized optical second harmonic saturated absorption lines in the pairs of molecular isotope iodine $^{127}I_2$, located in the area of 532 *nm*. Stabilizing the frequency of the second harmonic (f_{532}) laser by adjusting the length of the laser cavity will stabilize the main frequency of the radiation. Therefore, the radiation of this laser has two stable wavelengths – 1064 and 532 *nm*. The relative standard uncertainty of establishing the values of these wavelengths is 8.9 10^{-12}.

With the use of Nd: YAG/127I2 laser to stabilize the frequency comb of a femtosecond laser, it is required to include the wavelength range of 1000 *nm*, which can then be used in a given optical frequency standard radiation with a wavelength of 1064 *nm*.

The frequency difference f_b^{1064} between the frequency of optical standard (indicated by a thick line) and its adjacent spectral component (marked number N) is used to stabilize the entire frequency grid femtosecond laser. Equations for frequency, allowing the realized stabilization can be represented as follows:

$$f_{1064} = Nf_r + f_{ceo} + f_b^{1064},$$
$$f_{532} = 2f_{1064}. \quad (4)$$

Stabilization is accomplished by keeping the value f_b^{1064} unchanged and stable. Fig. 2 shows the relative position of an optical frequency standard and the emission spectrum of the femtosecond laser.

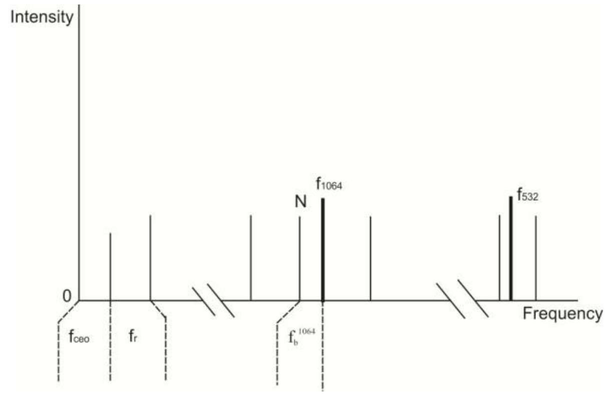

Fig. 2. Scheme of frequency stabilization of femtosecond laser spectrum

In fact, the stabilization condition variable f_b^{1064} is the condition that the absolute frequency of one of the harmonics of the frequency spectrum with a base frequency of ITU – 193 100 GHz (λ = 1552,52 *nm*). By tuning the dispersion properties of the cavity (i.e. changing of f_{ceo} value) the f_b^{1064} become value at which one of the harmonics coincides with the base rate. Thus, the system of equations (4) must be supplemented by the equation

$$Mf_r + f_{ceo} = f_{ITU} , \quad (5)$$

where M is integer.

Excluded from the system of equations (4) – (5) f_{ceo}, we obtain the equation for the frequency f_b^{1064}, which is the condition for the stabilization of the frequency spectrum

$$\left|f_b^{1064}\right| = \left|f_{1064} - f_{ITU} + (M - N)f_r\right| \quad (6)$$

Frequencies are taken modulo, because the sign of the beat frequency in these equations is not considered. If the values M and N determined, we know the numerical value of the beat signal, which would provide stabilization.

The resulting stabilization condition is independent of the optical standard and wavelength (frequency) of its radiation. Therefore, this condition is universal and can be used in any terms of stabilization of the frequency spectrum, which can be used to form the channel plan DWDM systems.

Block diagram of a device that can give practical effect to stabilize the frequency grid is shown in Fig. 3.

This combination of appropriate stabilization systems associated with a reference frequency synthesizer results in a stable frequency grid in the near infrared range. Using this optical synthesizer can provide a stable and reproducible frequencies for the full range DWDM, which overlaps the frequency grid of femtosecond laser, and therefore can be used in optical communications.

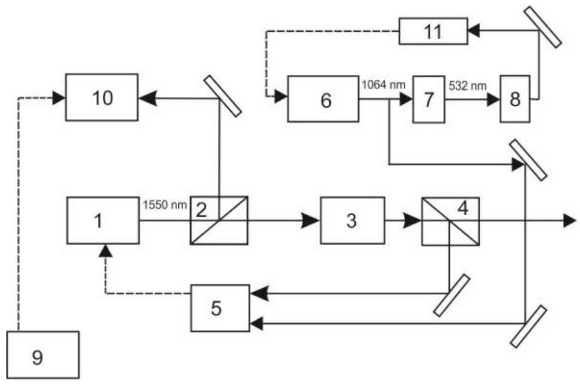

Fig. 3 Block diagram of stabilization femtosecond laser:

1 – femtosecond laser, 2 – beam splitter, 3 – fiber-based on photonic crystal, 4 – beam splitter 5 – device to stabilize f_{ceo}, 6 – Nd: YAG laser, 7 – nonlinear crystal, 8 – iodine cell, 9 – Rubidium generator , 10 – device to stabilize f_r, 11 – device to stabilize Nd: YAG laser

Stability in the infrared radiation is caused by the use of laser frequency stabilization by the natural rapper in the green part of the visible range.

The principle of freguency selection of optical channels

A. Selection of longitudinal mode laser chip

The problem of providing lasers with a single-frequency laser radiation is associated with the formation of the laser cavity itself. For large cavity length and with a significant excess of the threshold gain in the laser emission is observed a large number of longitudinal modes. Therefore, to achieve single-mode or few-mode radiation can be achieved by the formation of a composite resonator.

In this regard, this study examined the possibility of using the Fox-Smith Selector in the fiber laser to separate the longitudinal modes in the spectrum spaced at a predetermined distance from each other.

Fox-Smith Selector(block diagram is shown on Fig.4) developed [12, 13] for the selection of longitudinal modes in lasers with long cavity, for example, He-Ne laser, with a two-meter length of the resonator. In these lasers, a large number of longitudinal modes were excited, of which the Selector released one. The optical scheme of the resonator is shown in Fig. 4. The frequency interval between the three-mirror cavity resonances is usually chosen larger than the bandwidth of the laser, therefore value of L2+L3 must be small compared to the L1+L2 – cavity length. On the circuit in Fig. 4 one of the mirrors of the laser cavity is replaced by three mirrors M2, M3, M4. These three mirrors together form the secondary resonator, optically coupled to the main cavity, and is actually a mirror with selective frequency characteristics. The length of the resonator is equal to L2+L3, and determines the frequency spacing between bandwidths.

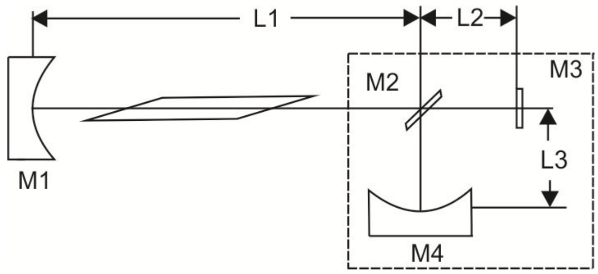

Fig. 4. Scheme of selection of longitudinal modes.
Three mirrors M2, M3, M4 form a tunable reflector for the laser

From the point of view of the theory of laser resonator, the device behaves as a single mirror, the reflection coefficient, which depending on the radiation frequency, can be continuously changed and has resonances of reflection and transmission. This mirror can be adjusted to the transmission of the selected longitudinal modes. Bandwidth (reflection) is determined by the Selector reflectance mirrors M2, while M3 and M4 are totally reflective.

In general, the Fox – Smith Selector is applicable in the case of it being smaller than the laser cavity, and in the case that it is greater than the length of the laser cavity, the length of the Selector. So in the case of a Selector in a laser cavity, operating in a multimode regime, the characteristic three-mirror reflection of selective reflector has the form shown in Fig. 4.

Application of the Fox-Smith Selector in a fiber laser can solve the problem of selection of the longitudinal modes, however, the parameters of the selector can have different values (Fig. 4).

This can generate several modes in the laser cavity, due to bandwidth of the active medium. In this case, the frequency separation between the modes

$$\Delta\nu = \frac{c}{2(\mathrm{L}_1 + \mathrm{L}_2)} \tag{7}$$

determined by the length of the resonator will be value $\Delta\nu_1$.

If a selector with dimensions much smaller than the size of the laser cavity, then in this case, the distance between the frequency bandwidths

$$\Delta\nu = \frac{\tilde{n}}{2(\mathrm{L}_3 + \mathrm{L}_2)} \tag{8}$$

will be equal $\Delta\nu_2$.

In this case, if the first match of the bandwidth selector with the line of the laser generation is in the center of the laser line, the following condition for the same bandwidth with a frequency selector longitudinal mode generation satisfy

$$\mathrm{m}\Delta\nu_1 = \mathrm{n}\Delta\nu_2, \tag{9}$$

where m and n integer numbers. In general, the second performance of this condition can be done outside the bandwidth of the active medium, which then leads to a single-frequency radiation. Thus, if the length of the selector does not provide a multiple ratio of its frequency bandwidths' distance to the length of the laser cavity intermodal distance, than all longitudinal modes will be excited in only one mode, which is the set selector.

The length along the optical axis of the mirror from splitter to highly reflecting mirror, is one part of the cavity length of the selector. The other part is determined by the direction of the reflected light from splitter mirror to the second mirror which sets it at a distance greater than the length of the laser cavity.

If the frequency range f_r of femtosecond laser is realized at about 100 *MHz,* then keeping frequency ranges of 100 *GHz* in the DWDM selector should divide every thousandth harmonic spectrum to it.

CPT as the basis for selective modulators with large capacity

Considering an other option to provide greater selectivity ability of multifrequency laser emission of femtosecond laser would be the effect of coherent population trapping (CPT) [14].

The effect of the CPT is a fundamental physical phenomenon and occurs when a medium interacts with two-frequency laser radiation. The main feature is that when the medium interacts with two beams, it can not emit or absorb radiation, and as a result there is a narrow gap in the fluorescence spectrum.

During the CPT resonance, entire population of Λ-system systems is distributed between the lower levels, therefore it called “trapping”. The applied light affect on each of the atomic transitions of the three-level system, but the system does not excite.

If to change frequencies of lasers ω_1 and ω_2 [15] will appear a transparency window but outside that window the radiation in the medium decays exponentially. The width of the transparency window decreases with increasing optical thickness and can become a homogeneous linewidth for the transition 2 – 1 (Fig. 5). This feature of the CPT is suggested to use as a physical basis for the development of frequency selectors.

Under certain conditions, atoms can be completely trapped in a dark state, where they cannot be excited by the applied light:

$(\omega_1 - \omega_{31}) - (\omega_2 - \omega_{32}) = \Omega_1 - \Omega_2 = 0$ (10)

where,

ω_{31}, ω_{32} – transition frequencies 3 – 1 and 3 – 2

ω_1, ω_2 – frequency fields.

Ω_1, Ω_2 – are the Rabi frequencies connecting the ground states and the excited states.

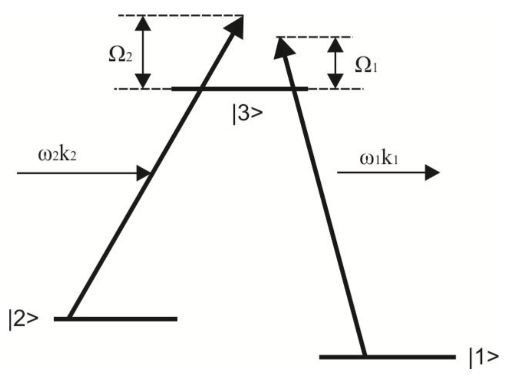

Fig. 5. Shows the three-level Λ-system

However, condition (10) [16] does not guarantee detection of CPT such as it occurs only for a certain intensity of light waves and the Λ-system necessary intensity is

$$I \gg I_c = I_t \frac{\Gamma}{\gamma} \quad (11)$$

Where I_t – the saturation intensity of the optical transition, Γ – transverse relaxation rate between the lower levels and γ – natural linewidth.

The main principle is to use CPT to control one optical radiation by another, but should be other options for the gap, allowing control by the frequency of one to vary the intensity of the radiation of the other. Considering the phenomenon of CPT, as the basis for the modulation of optical radiation through one another, the specifications of the original implementation of the modulation must be considered.

As the analysis shows, the conditions of usage of CPT for forming of the frequency benchmark and to the system of modulation of optical radiation are mutually exclusive. If, for example, for a frequency benchmark is needed to achieve a very steep slope gap, then for modulation the steepness of the slope should be much smaller and be linear over a wide range of frequencies.

The conditions of the CPT for modulation appear that the detuning of one radiation leads to changing of intensity other radiation, while not affecting other optical frequencies that are not involved in the formation of CPT. For the first time, the possibility of modulation of optical radiation through CPT has been presented in [15].

Conclusion

The paper discusses possible means of developing modern DWDM systems. Suggested to substitute existing set of semiconductor lasers with femtosecond laser as a source of broadband radiation spectrum. It also provides a block diagram of the stabilization femtosecond laser based on the radiation of Nd: YAG laser and iodine cells. It also discusses the most difficult issues in the construction of such systems, as well as the development of a frequency modulator, such as the current methods can not meet the selection requirements of 0.08 *nm* or less.

The devices used for separating and combining optical channels with specified width are implemented using the same physical principles, namely the suppression or enhancement of light due to the interference of the incident and reflected waves. Existing optical multiplexers and demultiplexers are mainly based on the basis of diffraction gratings, thin film filters, and a little less on the matrices of the diffraction waveguide and fiber Bragg gratings, the resolution of which is now coming to its physical limit.

It is possible that these physical effects can be used as a basis to build a fundamentally new multiplexer and demultiplexer, and that the phenomenon of CPT (coherent population trapping), will allow a much closer division frequency. This feature of the emission spectrum of a fiber femtosecond laser allows us to speak about its application in the existing DWDM systems (without changing the frequency plan of ITU).

As discussed in the paper, the use of femtosecond laser from the point of creating a new system clock frequency as channels of DWDM systems, it is proposed to use the radiation of a femtosecond laser stabilized by an external frequency wrapper.

Given that these laser sources, the number of discrete optical channels, may vary from a few hundred to a few million, and, therefore, the distance between frequency channels can be much smaller 10 GHz. This paper deals with the physical principles of optical frequency modulation, which independently impact each optical channel. In this regard, the paper also discusses the physical principles of such methods and devices, providing modulation and demodulation of optical channels created through the multifrequency radiation of a single laser source for their separation within the spectrum, and it also discusses the effect of CPT as a basis for creating modulation and demodulation devices for laser radiation.

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